Available online at www.sciencedirect.com
ScienceDirect

Icarus 184 (2006) 436–451

ICARUS

www.elsevier.com/locate/icarus

Formation of a terraced fan deposit in Coprates Catena, Mars

Catherine M. Weitz [a,*], Rossman P. Irwin III [b], Frank C. Chuang [a], Mary C. Bourke [a],
David A. Crown [a]

[a] *Planetary Science Institute, 1700 E Fort Lowell Road, Suite 106, Tucson, AZ 85719-2395, USA*
[b] *Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Independence Avenue at 6th Street SW, Washington, DC 20013-7012, USA*

Received 11 January 2006; revised 18 May 2006

Available online 11 July 2006

Abstract

We have studied a terraced fan deposit with unique characteristics located within a trough of Coprates Catena. The fan has an average length of 6.8 km, and is approximately 44 km^2 in area and 18 km^3 in volume. The fan's broad contributing valley is approximately 35 km long and it noticeably increases in depth about 12.8 km before it intersects the trough, where a rounded knickpoint marks the transition between flat-floored upstream and V-shaped downstream cross-sections. A 14-km-long channel with no apparent source enters the contributing valley from the south. A much smaller sinuous channel has incised along a smaller V-shaped valley in the uppermost eastern portion of the fan deposit. We explored several possible origins for the terraced fan, including mass wasting, volcanic flow, alluvial fan, and delta. We propose that water sourced from volcanic melting of ice eroded and transported material along the contributing valley. This material was then deposited as a delta in a lake within the trough. The concentric terraces are most likely the result of shoreline or ice cover erosion during drops in lake level. A light-toned layered deposit to the east of the fan deposit along the floor of the trough may represent a sedimentary unit formed during the terminal stages of the lake. Although other terraced fans have been identified on Mars, the Coprates Catena fan is unique because it has many more terraces and its surface was incised by a channel and associated valley. The identification of several other valleys to the east suggests that volcanic melting of volatiles during the Hesperian Period created favorable conditions for water flow along the plains in this region.

Keywords: Mars, surface

1. Introduction

We have studied a terraced lobate fan deposit centered at 15.0° S, 299.7° E within one of the troughs of Coprates Catena (Fig. 1) in order to investigate the role that water may have played in its formation. Only about a dozen of these terraced fan deposits have been identified on Mars (Ori et al., 2000; Cabrol and Grin, 2001; Malin and Edgett, 2003; Irwin et al., 2005), although their small sizes make them difficult to identify with the current orbital data sets. Moore and Howard (2005) have identified several dozen alluvial fans in highland craters. The few fan deposits that do not have terraces and are not classified as alluvial fans in highland craters (e.g., Eberswalde crater, Nili Fossae) have been interpreted as deltas in standing bodies of water (Malin and Edgett, 2003; Moore et al., 2003; Fassett and Head, 2005; Bhattacharya et al., 2005; Irwin et al., 2005). The surfaces of some of these fan deposits are now marked by inverted terrain (including crosscutting ridges representing former channel fills), more irregular fan shapes that reflect channel avulsion and discrete lobe extension, and shallower slopes relative to those of terraced fans. The terraced fan in Coprates Catena is unique among the currently known terraced fans because a smaller channel and associated valley incised the surface of the terraced fan deposit. The terraced fan has received extensive image coverage from both Mars Global Surveyor (MGS) and Mars Odyssey (MO), and it appears moderately free of dust, providing a detailed view of its morphology.

Although valleys and channels are numerous across the martian surface, few are associated with evident terminal deposits

---

[*] Corresponding author. Address for correspondence: 1138 N. Randolph Street, Arlington, VA 22201, USA. Fax: +1 (520) 622 8060.
E-mail address: weitz@psi.edu (C.M. Weitz).

0019-1035/$ – see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2006.05.024

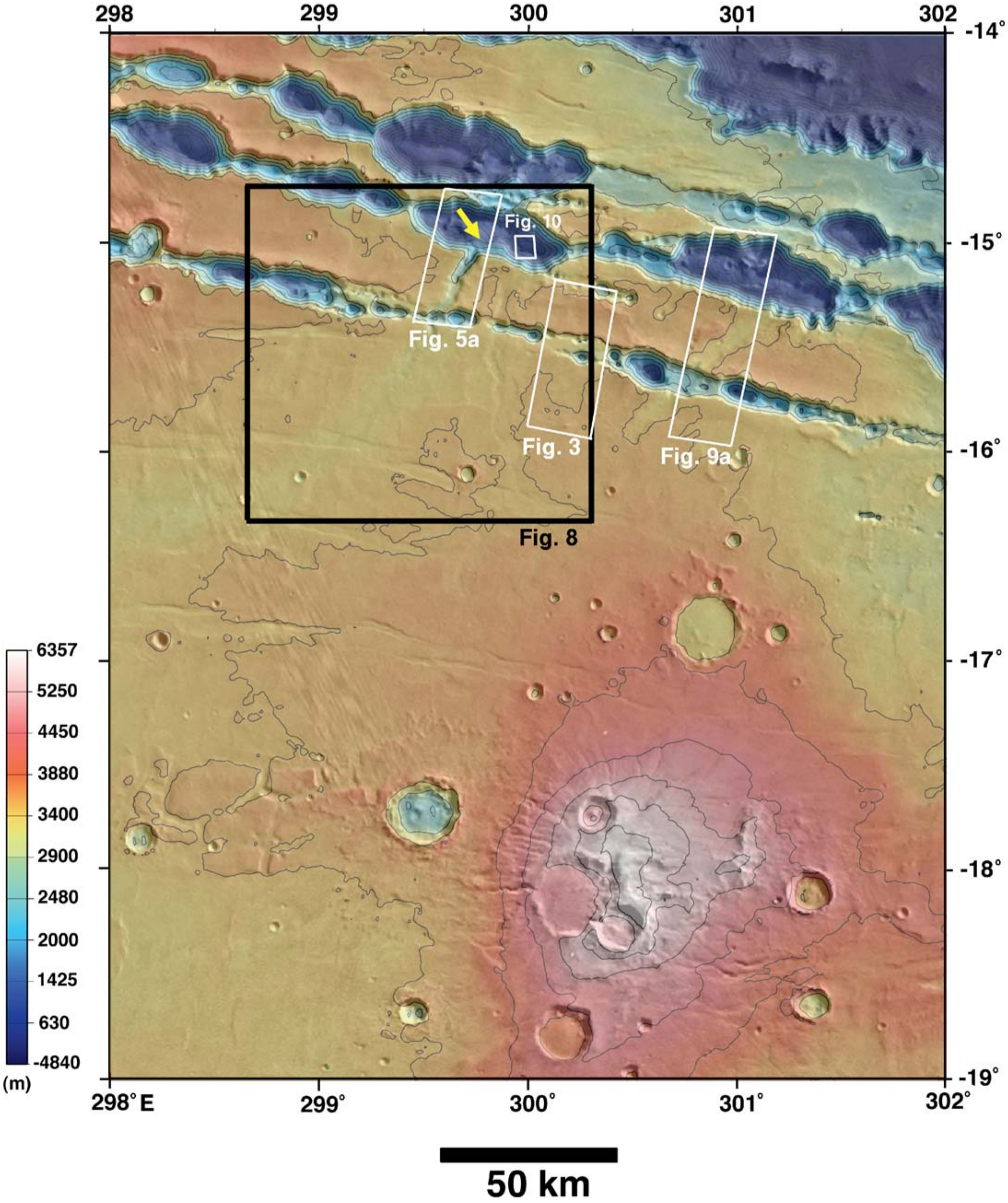


Fig. 1. MOLA topography at 128 pxl/deg superimposed on Viking Orbiter MDIM of the study region. Contour intervals are spaced at 500 m. Color of topography has been skewed to show more color variations above 500 m and all set to a similar color below this elevation. Boxes indicating the locations of later figures are shown. Yellow arrow shows location of terraced fan.

(Malin and Edgett, 2003; Irwin et al., 2005). The scarcity of positive-relief deposits could indicate that valleys formed primarily by corrosion with minimal transport of clastic sediment. Alternatively, density currents or post-depositional processes may have been highly effective at distributing sediment within a basin, or flows may have been too ephemeral and variable to yield a stable lake level that would favor accumulation at the valley mouth. Consequently, this fan potentially represents one of only a few opportunities to study a depositional unit associated with a valley and channel system. The fan deposit also provides potential evidence for a high level lake stand, as well as the persistence of water required for the development of terraces.

2. Data sets

In this study we use Viking Orbiter, MGS, and MO mission datasets. A Viking Orbiter Mars Digital Image Mosaic (MDIM) 2.1 at 256 pxl/deg resolution (∼231 m/pxl) of the study region was used as a base map on which higher resolution images were placed. Data analyzed included MGS Mars Orbiter Camera (MOC) narrow angle images, MGS Mars Orbiter Laser Altimeter (MOLA) digital elevation models and orbital tracks, and MO Thermal Emission Imaging System (THEMIS) daytime and nighttime infrared (IR) images (∼100 m/pxl resolution) and visible wavelength (VIS) images (∼18 m/pxl resolution). A combination of the daytime and nighttime THEMIS

IR images can aid in assessing the thermal inertia of units. For example, units that are dark in the daytime IR images and bright in the nighttime IR images are likely to be higher in thermal inertia, representing rockier or less dusty surfaces. To assess the topography of the fan surface and the study region in general, we used MOLA Mission Experiment Gridded Data Records (MEGDR) digital data at 128 pxl/deg resolution (∼462 m/pxl) and individual Precision Experiment Data Record (PEDR) altimetry data with a footprint diameter of 170 m and horizontal spacing of ∼300 m (Smith et al., 2001).

All MOC and THEMIS images were processed from raw to geometrically calibrated, noise-reduced, map-projected images using the Integrated Software for Imagers and Spectrometers (ISIS) software developed by the U.S. Geological Survey (USGS ISIS website, http://isis.astrogeology.usgs.gov). Of the ten bands available in THEMIS daytime IR images, we use the best-calibrated band 9 (12.57 µm-centered) image. For THEMIS VIS images, we use the band 3 (0.654 µm-centered) image. Each PEDR binary altimetry file containing latitude, longitude, and elevation data was converted to an ASCII-text file using Interactive Data Language (IDL) software. Once coregistered, all image data were imported into Adobe Photoshop and individually stretched to produce smooth transitions in brightness across neighboring images.

3. Geologic features of Coprates Catena

Fig. 1 shows the regional area of study, which includes the Coprates Catena fan deposit. A broad putative volcano with numerous valleys along its slopes dominates the southern portion of the study area. Linear chains of pit craters and small troughs trend NW–SE dominate the upper portion of the study region. In the following sections, we discuss specific geologic features that may have associations with the formation of the fan deposit or that indicate water activity in the region.

3.1. *Putative volcano*

An unnamed degraded mountain interpreted to be volcanic in origin dominates the geology to the south of Coprates Catena. Saunders et al. (1980) originally interpreted this structure as a highland shield volcano with radiating lava channels on its flanks. This putative volcano is highly disrupted by several large impact craters. Based upon MOLA altimetry, the volcano exhibits about 3.4 km of relief above the surrounding plain and its flanks extend out for perhaps 150 km. The apparent caldera of the volcano is 23.5 km in diameter and is breached at the west by a valley. Alternatively, this could be a large impact crater that, along with the crater just to the southeast, destroyed any former caldera that may have been present.

Similar to the paterae seen in the southern highlands of Mars (Plescia and Saunders, 1979; Greeley and Spudis, 1981; Crown and Greeley, 1993), this volcano also has an extensive system of valleys that extend radially along its flanks. However, the gross morphology of this proposed volcano, with its higher relief and lack of a distinct central summit caldera, differs from the broad, flat profiles of large highland paterae in the circum-Hellas highlands. The valleys appear predominantly to pre-date the large impact craters on the flanks. The nighttime THEMIS IR image (Fig. 2) shows the valleys best by their darker appearance, perhaps due to accumulation of fines in the channel floors. THEMIS VIS and MOC images along the flanks support the interpretation that brighter dust and bright linear dunes cover the floors of the valleys.

It is possible that geothermal heat and volcanic activity melted ice near Coprates Catena, mobilizing water that eventually began to carve the terraced fan's contributing channel and valley. However, none of the valleys along the volcano flanks extend to the contributing valley, which would argue against the volcano being the source for the water that formed the fan in Coprates Catena. Further discussion of the fan formation will be discussed in a later section.

3.2. *Troughs and plains*

Coprates Catena is a smaller trough system parallel to the main Coprates Chasma system. Coprates Catena troughs are aligned with pit craters that vary considerably in length and depth. Another smaller parallel system of pit craters and troughs is located to the south of Coprates Catena. Linear grabens that parallel the NW–SE trending trough systems are also visible to the south (Fig. 2). It is likely that the troughs and pit craters to the north began as similar graben systems. It is also plausible that the pit craters broaden and evolve with time into the larger, more elongate troughs, which in turn merge and continue to increase in size to eventually form chasmata. The precise mechanism for this evolution to larger depressions remains unknown, but it likely reflects continued extension of the Valles Marineris region. Alternatively, some have suggested that the pit chains and troughs could be unrelated to the development of larger troughs and chasmata (Schultz, 1989; Lucchitta et al., 1990).

Mege et al. (2003) point out that the smaller chasmata/troughs display little evidence for faulting and are aligned with pit chains, and therefore they favor an origin by volcanic collapse due to magma withdrawal in the subsurface. Dike emplacement that produced the narrow grabens to the south of the chasma could have also melted any neighboring ice, which could then lead to formation of the channel and valley, although this does not explain why ice would only be concentrated at this location.

The trough that contains the terraced fan is 47 km long and 15 km wide. The minimum elevation in the trough is 0 m, which occurs in two small pit craters, one on the eastern and one on the western side of the floor. The maximum relief from these low spots to the top of the wallrock is 3.6 km. The upper wallrock has the typical spur and gully morphology commonly seen in Valles Marineris (Lucchitta et al., 1992), whereas the lower slopes are covered by mass wasting debris.

A few of the troughs and pit craters have a halo of thermally dark material in THEMIS nighttime IR images (Fig. 2). There is no apparent bright material visible in the corresponding THEMIS daytime IR image. The thermally dark material

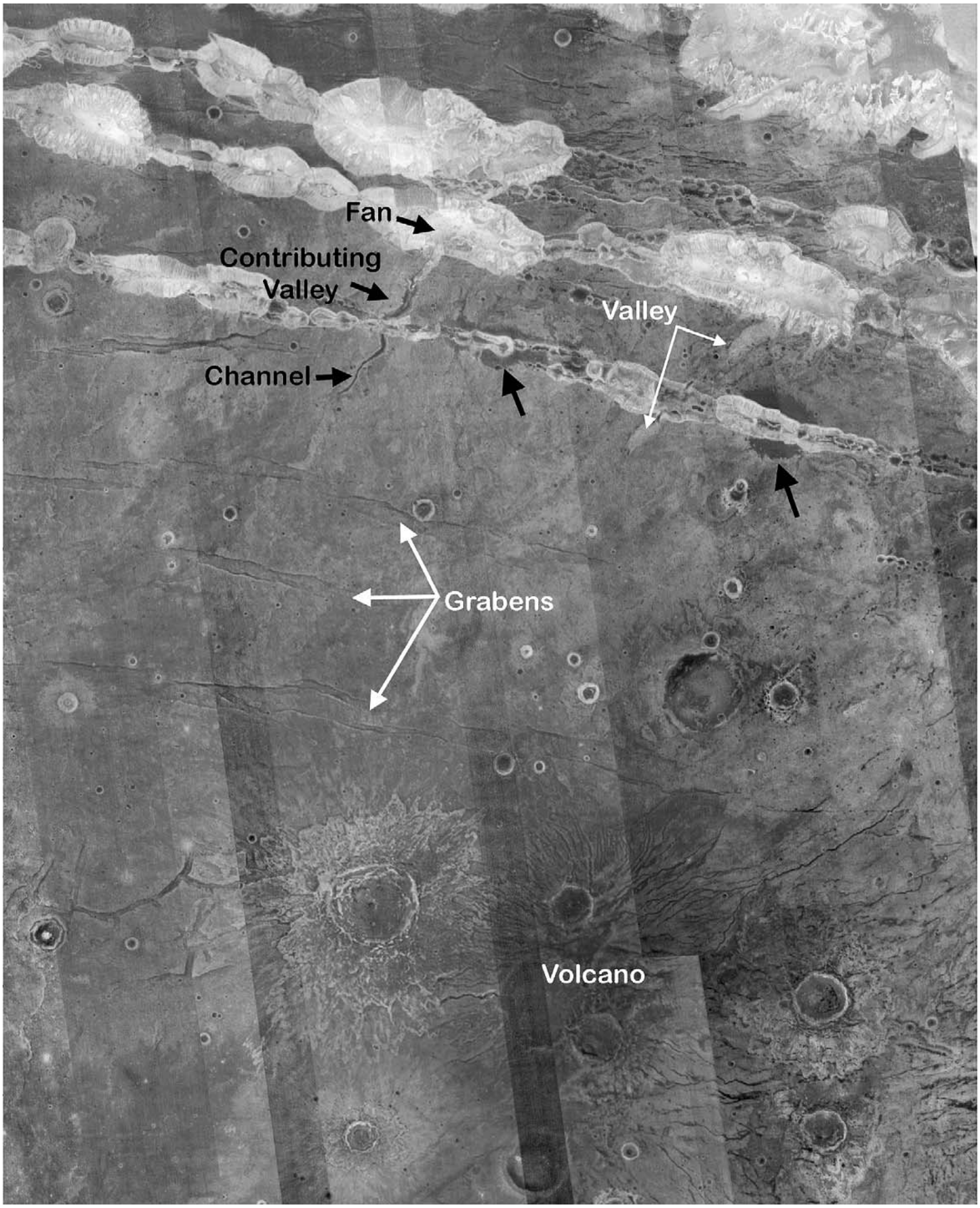


Fig. 2. Mosaic of THEMIS nighttime IR images for the same region shown in Fig. 1. The terraced fan deposit is barely visible because it has the same brightness as the adjacent trough floor materials. Black arrows point to relatively dark material with low thermal inertia that surrounds several troughs and pits.

could represent fine-grained or smoother material relative to the adjacent plains. Dust would be a plausible explanation for the low brightness temperature in the nighttime IR images, although we are aware of no geologic explanation that would favor dust accumulation around these particular troughs and pits. A THEMIS VIS image that covers these dark halos (Fig. 3) reveals a smoother, less cratered surface compared to the adjacent plains. If pit craters and troughs form by volcanic collapse as proposed by Mege et al. (2003), then perhaps the dark halos are younger lava flows or pyroclastic deposits emplaced as part of the same volcanic activity that formed the pits and troughs. As the pits and troughs continue to increase in size by further extension, these smooth surfaces would become engulfed and removed, possibly explaining why the larger troughs and chasmata do not have similar dark halos in the THEMIS nighttime images. If volcanism is the cause of the pit and trough formation, as well as these dark halos, then volcanism in the plains would be a plausible heat source for melting of ice that subsequently resulted in the formation of the valleys, channels, and fan deposit described in the next sections.

Fig. 3. Portion of THEMIS VIS image V06544001. Black arrows identify material that appears dark around troughs and pits in Fig. 2. These units appear much smoother and with fewer craters than the adjacent plains, perhaps reflecting young lava flows or pyroclastic deposits emplaced during formation of the pits and troughs. Also visible are segments of a bright ring that could be remnants of a former crater (white arrows).

One final feature of interest in the plains is a bright ring seen only in the MOC and THEMIS visible images (Fig. 3). The circular feature could be due to a degraded impact crater that has been filled over time. The higher reflectance of the rim is difficult to explain. The rim surface does not appear morphologically distinct from the adjacent plains, so the brightness likely reflects an albedo difference in the material. The concentration of these higher reflectance materials along the original circular structure cannot be easily explained, however. As we note in the next sections, bright material seen elsewhere in Coprates Catena is most likely correlated to areas where water once existed, and a similar explanation may apply to this circular structure as well. If so, then this region may have experienced multiple locations where water flow and deposition emplaced widespread material.

3.3. Terraced fan deposit

The terraced fan deposit (Fig. 4) is not perfectly symmetrical in appearance, but rather appears more irregular on the eastern side compared to the smoother fan shape on the western side. The northern edge is not a distinct boundary because it appears partially buried by dunes and talus material from the adjacent northern wallrock. The fan deposit has a maximum width of 7.9 km and length of 8.6 km, and it emanates from a 35-km-long contributing valley that cuts through the plains before terminating in the trough. The fan radius varies from 5.1 km at the eastern edge to 8.6 km at the northern tip. We can estimate the area of the deposit by assuming a symmetrical fan shape that makes up a portion of a circle. The area is $0.5\theta(R)^2$, where θ is the angle in radians measured between the two fan sides and R is the radius. If we use an average radius of 6.8 km and a θ of 110° or 1.92 radians, then an approximate area for the fan is 44 km^2.

The fan deposit has a maximum thickness (H) of 1.4 km based upon MOLA topography, and the top of the deposit lies 1.4 km below the top of the trough's southern wall. Using an average thickness that is one-third the height of the fan, which is more appropriate for a cone shape, then the volume is 21 km^3. This is the same volume as that calculated if we use a cone sector with an angle of 110° or 110°/360° $(1/3\pi R^2 H)$. This volume estimate includes both the fan deposit and the underlying volume of wallrock upon which the fan has been emplaced. Therefore, to subtract out the volume of wallrock, we use the slope of 29° derived from MOLA topography of the adjacent wallrock and the same thickness of 1.4 km to calculate a radius of 2.5 km. The cone sector of underlying wallrock volume is then 110°/360° $(1/3\pi(2.5)^2 1.4)$, which equals 2.8 km^3. Thus, the volume we estimate for the fan deposit is 21 km^3 minus 2.8 km^3, or ∼18 km^3.

Although the fan surface is irregular and contains many steep scarps, slopes average ∼8° along its surface, compared to ∼29° for the adjacent wallrock slopes. There is a break in slope along the fan, with the upper part a few degrees steeper than the lower part (Figs. 5a, 5b). These steep slopes are consistent with debris-flow dominated fans on Earth, which typically have slopes above 5° (Blair and McPherson, 1994). However, the longitudinal gradient on the Coprates terraced fan is an average of steep scarps and terrace surfaces with lower slope, so the mean longitudinal gradient is not necessarily informative of depositional process. Moore and Howard (2005) measured gradients of 2° for alluvial fans in Holden Crater and elsewhere. They suggest the martian fans fall in a range typical of fluvially deposited terrestrial alluvial fans dominated by gravelly sediment.

There are concentric scarps across the surface of the deposit producing a terraced morphology (Fig. 4a). Several of the scarps near the upper portion of the fan deposit appear relatively

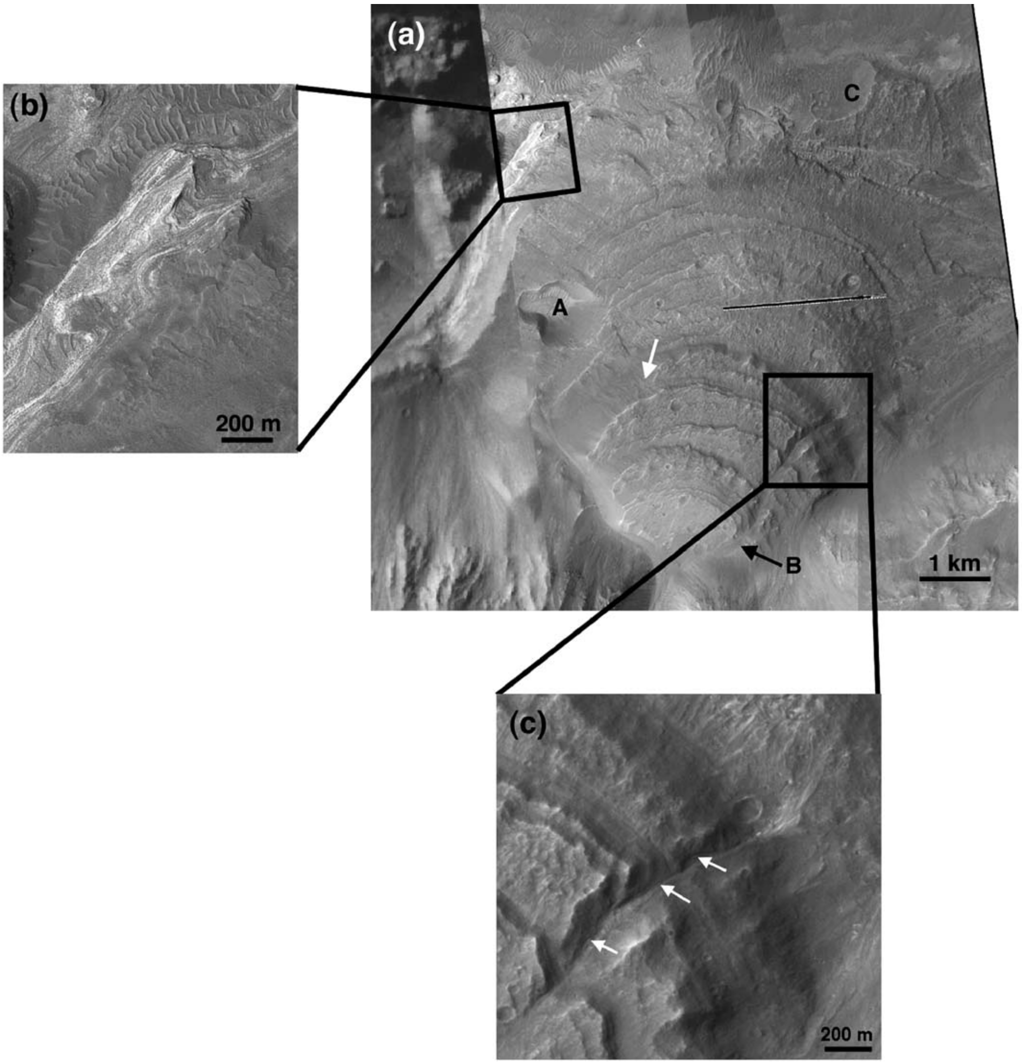
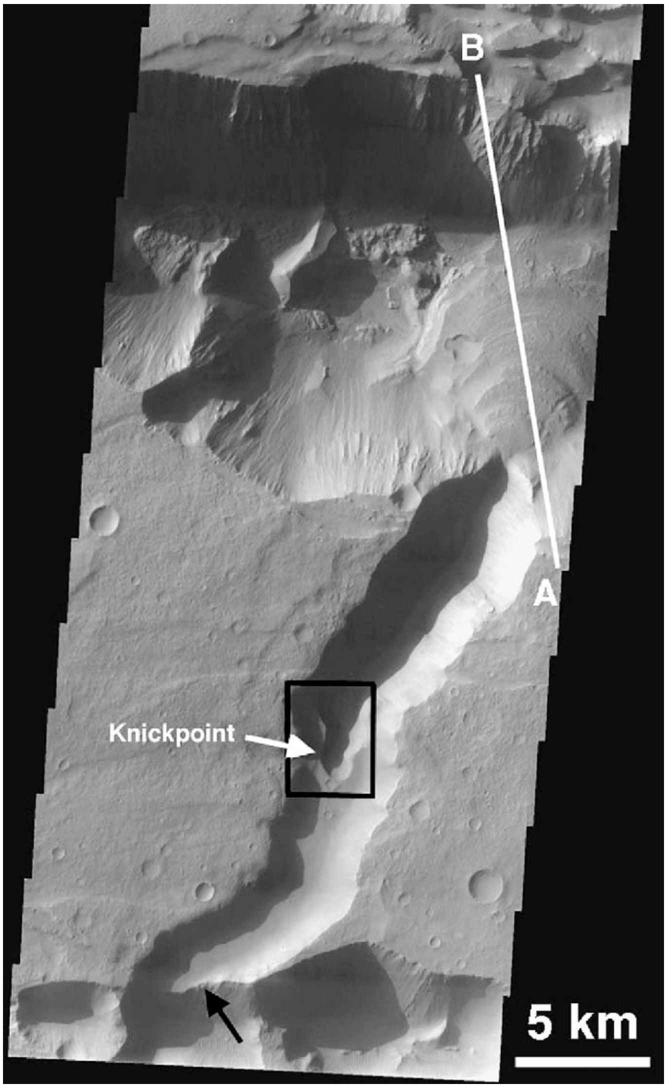


Fig. 4. (a) Terraced fan deposit in a portion of THEMIS visible image V03548003 and MOC images R0300723, M0400649, and S0601699. A possible collapse pit (A) disrupts several of the terraces in the west. The smaller valley and channel that incise the eastern portion of the fan appear to initiate to the northeast (B) of the termination of the larger valley that enters the trough. An irregular distal edge with possible collapse features is seen in the northeast of the fan (C). Although most of the terraces can be traced radially across the fan, some of the layers appear to abruptly end (white arrow). (b) Enlarged detailed image of edge of fan deposit that shows light-toned, finer scale layering. (c) Enlarged detailed image of valley and channel (white arrows) that incised the fan surface. At the termination of the valley and channel is a small bright deposit.

steep compared to scarps at lower elevation. The scarps are not sharp, smooth breaks in slope, but rather jagged elongate knobs that point radially outward from the valley mouth. These knobs could reflect either the original depositional surface or post-depositional modification by the wind. Using high-resolution MOC images R0300723 and M0400649 that cover the eastern side of the fan deposit, we count at least 25 prominent scarps on the surface of the deposit, although there appear to be additional thinner and less prominent scarps as well. The number of scarps is substantially greater than at other terraced fan deposits on Mars, which appear to have roughly a dozen or fewer scarps. The narrow-angle MOC public request image S0601699 that covers the western portion of the fan reveals finer-scale light-toned layering along the fan's edge in one particular area (Fig. 4b). Several of the larger scarps that can be seen along the uppermost portion of the fan in the east cannot be traced to the western side of the fan (Fig. 4a).

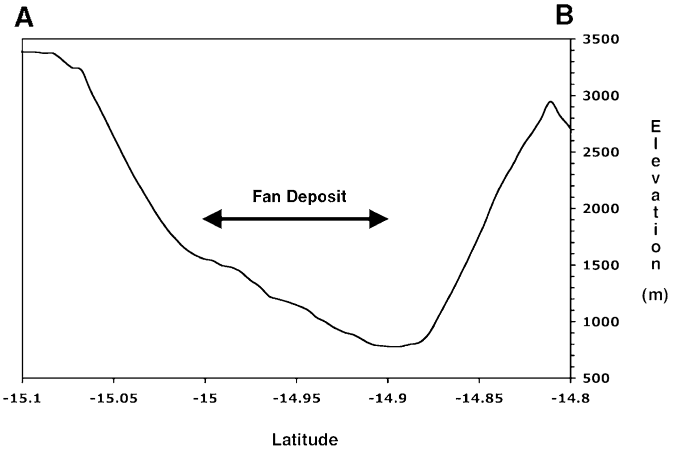
The small size of the fan deposit makes it difficult to determine its age from crater statistics. Nevertheless, there are numerous small impact craters (20–60 m diameter) on the fan deposit. A rounded depression on the western side of the fan (Fig. 4a, A) could either be a collapse pit or a degraded impact crater. The depression appears to be two circular holes merged together, which is more typical of pit craters. It is difficult to determine if the pit crater initiated on the trough floor and propagated into the fan deposit, or if the depressions formed only in the fan deposit by post-emplacement collapse. A scalloped edge along the northern tip of the fan deposit also could result from post-emplacement slumping and collapse (Fig. 4a, C).

The THEMIS nighttime IR images that cover the fan deposit show brightness values similar to that seen elsewhere along the trough floor and slopes, indicating similarly high thermal inertias. Compared to the surrounding plains outside the trough, the floor and fan deposit are brighter due to exposure of rougher or

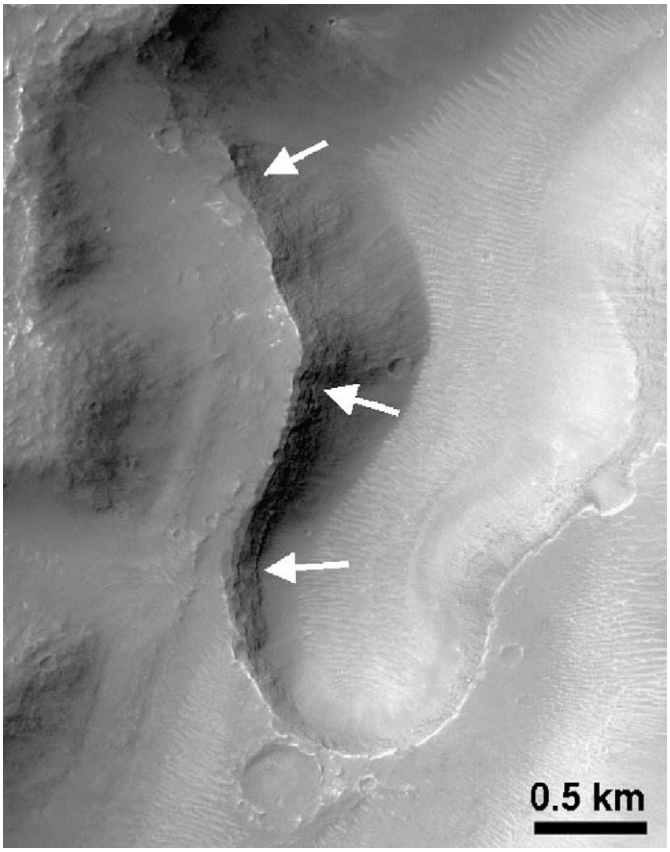


(a)

Fig. 5. (a) Portion of THEMIS VIS V03548003 that covers the trough, fan deposit, and the northern segment of the valley that extends into the trough. The rounded knickpoint along the valley indicates where a sudden drop in elevation occurs. Black arrow indicates where a younger segment of a trough system to the south has cut through the valley. Black box shows location of (c). (b) MOLA profile ap14145 across the fan deposit. Location of the profile is shown in (a). Slopes average 8° along the fan deposit, compared to 29° for the wallrock. (c) Portion of MOC image E0301211 showing resistant layers along the knickpoint and valley walls.



(b)



(c)

Fig. 5. (*continued*)

more indurated surfaces. In the THEMIS daytime IR images, the fan deposit, trough, and plains all have similar brightness. The rounded depression on the western portion of the fan is visible in the nighttime IR images as a darker spot and in daytime IR images as a bright spot, consistent with infilling by dust and dunes.

For comparison to one of the other terraced fans on Mars, we show a similar deposit in the Memnonia region (Fig. 6). Ori et al. (2000) originally studied this deposit using Viking Orbiter images. The deposit is located on a crater floor at the mouth of a short contributing valley that is incised into the crater wall. Although Ori et al. (2000) interpret the deposit as an alluvial fan, they suggest that the terraces could indicate the presence of shorelines from a former standing body of water. Looking at the more recent MOC, THEMIS VIS, and THEMIS daytime IR images of this deposit (Fig. 6), the Memnonia fan appears more subdued in topography, and the terraces are not as pronounced or as numerous as those in the Coprates Catena fan deposit. No channel is visible either in the valley or on the fan surface. The more subdued surface and lack of features in comparison to the Coprates Catena fan deposit may be attributed to more dust cover that has also blanketed the neighboring cratered highlands. Dark wind streaks are prominent along portions of the fan deposit as well. Nevertheless, its general morphology, which in-

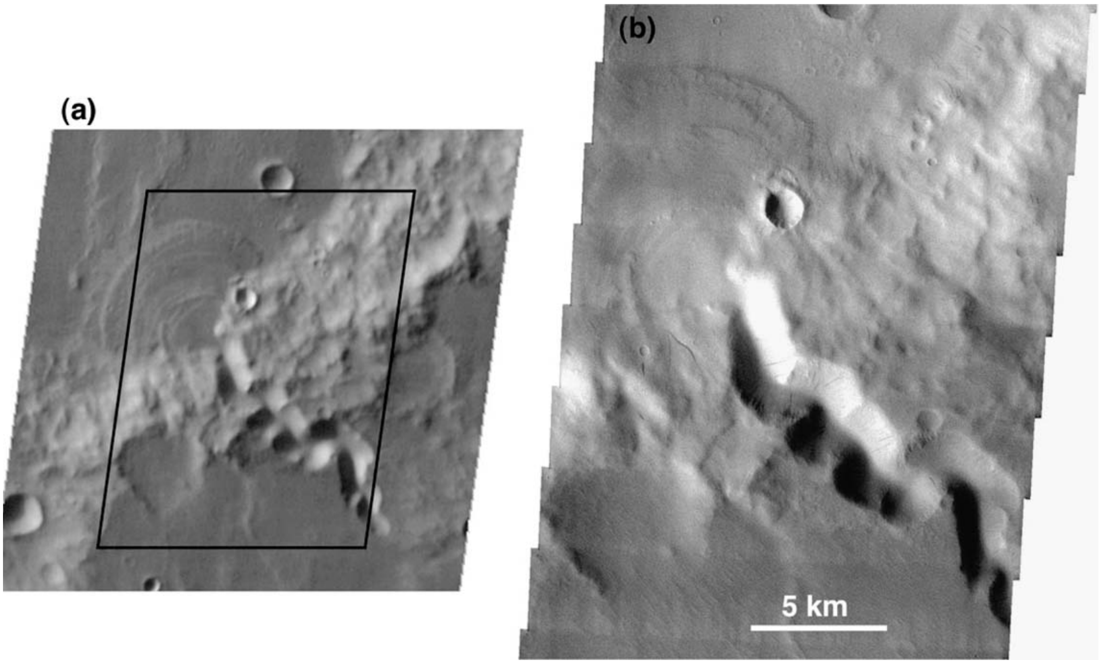


Fig. 6. (a) Portion of THEMIS daytime IR image I04674005 and (b) portion of THEMIS VIS image V09044001 of a similar terraced fan deposit in a crater in the Memnonia region (8.7° S, 200.4° E). Like the terraced fan deposit in Coprates Catena, this fan initiates where a short valley encounters a drop in elevation. Large amounts of dust obscure the surface of the fan deposit, making it difficult to identify any possible channels associated with the fan and valley. Black box in (a) shows location of (b).

cludes a cone-shape and terraces, as well as its location at the mouth of a valley, is consistent with a similar origin to the fan deposit in Coprates Catena.

3.4. Valleys and channels

A broad contributing valley approximately 35 km long increases in width and depth downstream, and terminates where it enters the trough, coincident with the fan head (Fig. 7). At the intersection with the trough, the contributing valley has a maximum width of 4.7 km and depth of 1.2 km. There are no tributaries associated with this valley. It is one of several valleys that we have identified in the area that trend northeast, roughly perpendicular to the NW–SE trough system of Coprates Catena.

A smaller contributing channel enters into the contributing valley to the south, but is not visible within the valley. The channel maintains a constant width of 760 m for 14 km length before broadening into a flat-floored valley. Its relatively large width and apparent flat-floor morphology could also imply that it is a smaller valley, but we cannot discriminate between a valley or channel origin with the available data sets. The channel has no obvious source to the south visible in the MOC or THEMIS images.

A much smaller and sinuous channel is incised along a V-shaped valley in the uppermost eastern portion of the fan deposit (Fig. 4). Both the fan head valley and the channel within it are oriented along the same northeast trend as the larger contributing valley flowing into the trough. In the visible images, there is a bright feature about 300 m in length at the termination of the smaller channel and valley (Fig. 4c). The valley is 0.3 km wide and 3.2 km long. The incision of the small valley does not begin at the apex of the fan where the larger valley enters the trough, but rather slightly to the northeast near the top of the uppermost fan scarp (Fig. 4a, B). Talus from the adjacent wallrock could have buried the small valley closer to the fan apex, resulting in its apparent origin to the northeast of the larger valley.

MOLA topography superimposed on the THEMIS nighttime and daytime IR images is shown in Fig. 8. The topography reveals a subtle, broad low that extends to the southwest beyond the contributing channel and valley. This broad low apparently localized overland flow to form the deeper contributing valley at its present location.

Approximately 12.8 km before it intersects the trough, the valley noticeably increases in depth and there is a corresponding change in slope from nearly horizontal to 4°. This increase in depth and slope corresponds to where the valley transitions from a flat-floor to V-shape at a rounded knickpoint (Fig. 5a). Knickpoints in terrestrial channels can occur either when a lowering of the base level forces a river to readjust by forming a short oversteepened segment immediately upstream from the site of the base-level decline, or due to downcutting into a resistant layer (e.g., Ritter et al., 1995). The rounded knickpoint here is suggestive of a change in lithology between the shallower southern valley floor and the deeper northern floor, with a more resistant material overlying a less resistant material. The THEMIS VIS image V0354003 and MOC narrow-angle image E0301211 confirm that there are recognizable, presumably more resistant layers seen along the upper wallrock of the valley that can be traced to the same height where the knickpoint is located stratigraphically in the valley floor (Fig. 5c). Upper resistant layers along Valles Marineris wallrock have been noted elsewhere by others (McEwen et al., 1999; Malin and Edgett, 2000; Beyer and McEwen, 2005), so this area is not unique

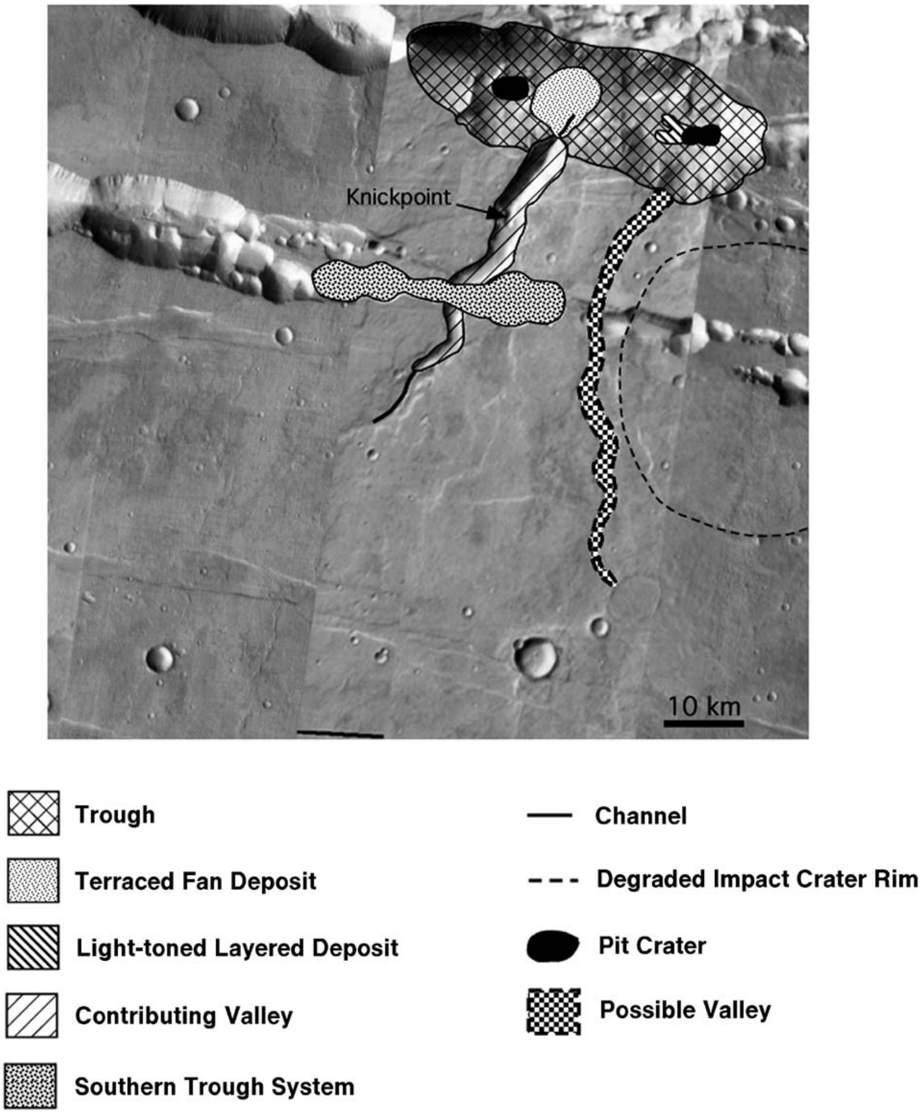


Fig. 7. THEMIS daytime IR mosaic with a geologic sketch map showing features discussed in the text.

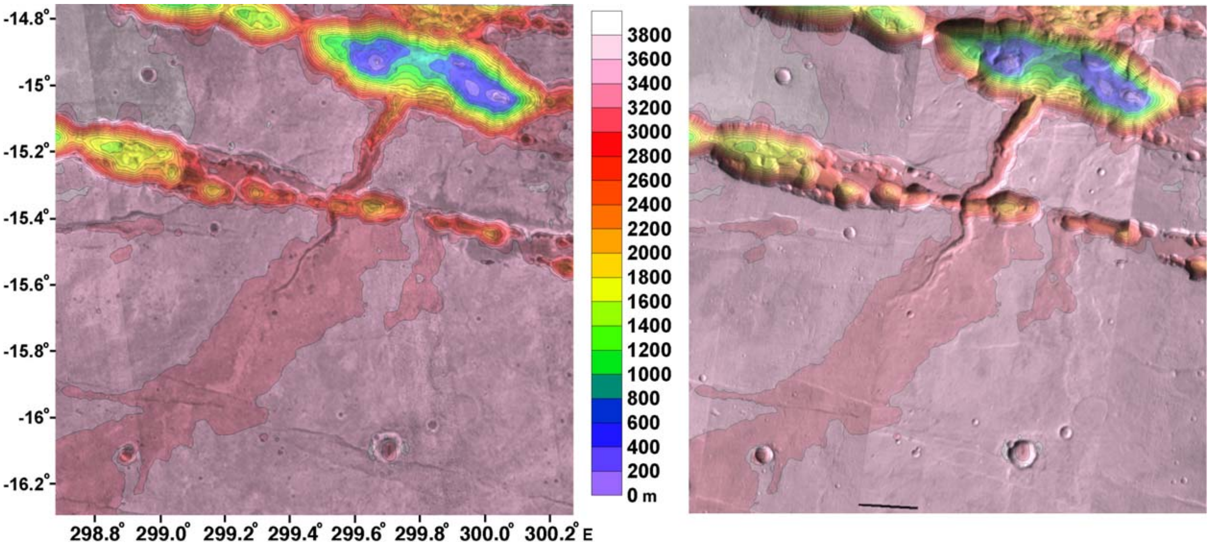


Fig. 8. MOLA topography (128 pxl/deg) superimposed on THEMIS nighttime IR mosaic (left) and daytime IR mosaic (right).

and these layers likely represent the same basaltic lavas seen throughout this region. Therefore, we interpret the knickpoint in the contributing valley to reflect undermining of these resistant layers by water movement. Over time, the knickpoint migrated upstream along the valley, creating a steeper V-shaped valley downstream of the knickpoint due to enhanced erosion of the underlying softer material. The great increase in width with distance downstream in this single-stem valley with no tributaries probably suggests a period of base level stability, which we interpret to be due to the resistant layers.

The contributing channel that flows through the plains, and also the flat-floored portion of the contributing valley, both appear relatively darker than the adjacent plains in the THEMIS nighttime IR image (Fig. 2). In contrast, the deeper V-shaped portion of the contributing valley appears brighter. The darker segments likely correspond to locations where dust has accumulated, whereas the deeper valley has rough wallrock along its slopes, producing a brighter appearance, or higher thermal inertia relative to the plains. The wallrock along the trough and other steep depressions all have greater brightness in the THEMIS nighttime images because of the rougher surfaces and lower dust concentrations.

The contributing valley that extends into the Coprates Catena trough and terminates at the fan deposit is approximately contemporaneous with the pits and troughs of this region. The plains are mapped as early Hesperian in age, which places the pits and troughs around this age or slightly younger (Lucchitta et al., 1992). Although both the valley and fan deposit are younger than the particular trough within which they are associated, to the south another NW–SE system of troughs and pit craters has disrupted the valley by cutting though it (Fig. 7). The western edge of the valley is still visible at the intersection with the trough, but the eastern edge has been partially removed by collapse associated with formation of the trough (Fig. 5a). The topography of the valley floor is the same to the south and north of the trough. Based upon these crosscutting relationships, the valley is older and was disrupted by this southerly trough system, but it is younger than the more northerly trough system. Hence, valley formation is contemporaneous to trough formation.

We can approximate the volume of the valley downstream of the knickpoint for comparison to the volume of the fan deposit. If we assume a pyramid shape that is cut in half for the valley between the knickpoint and the edge of the trough, then the volume would be $1/6WHL$, where W is the width of the valley where it enters the trough, H is the height where it enters the trough, and L is the length (12.8 km). If the height is 1.2 km and width is 4.7 km where the valley enters the trough, then the volume of this segment of the valley is equal to 12 km^3. This volume estimation is consistent with erosion and removal of this portion of the valley downstream (north) of the knickpoint to account for two-thirds of the material that composes the fan deposit, with the portion of the valley upstream (south) of the knickpoint contributing the remainder of the material to the fan deposit.

A possible valley is mapped to the east, and it too appears to extend into the trough (Fig. 7). There is no disruption of the wallrock along the location where this valley intersects the trough, either because it did not reach the trough or the valley pre-dates trough formation and any subsequent trough widening. MOLA topography (Fig. 8) shows a broad low that corresponds to the southern portion of this valley. Unfortunately, without high-resolution narrow-angle MOC images, this subtle feature is difficult to interpret in more detail.

One additional valley in the region is located further to the east in an adjacent trough (Fig. 2). MOLA topography (Fig. 1) indicates a relative low associated with a linear feature that has the same SW–NE trend as the fan deposit valley system. If it is a valley, then it appears to originate in the plains and extend to the northeast until terminating at another trough. It is disrupted by the southernmost trough and pit crater system, indicating that it pre-dates this system. The lack of any disruption of the wallrock where the valley enters the larger northerly trough suggests that it also pre-dates this trough. The valley stands out in the THEMIS nighttime IR images as a brighter unit than the adjacent plains (Fig. 2). What is intriguing about this possible valley is that its floor has a bright deposit seen in a MOC narrow angle image (Fig. 9). If water was involved in the formation of the valley, then it is plausible that salts or other soluble minerals would have been carried along by the water and then settled out or evaporated as the water was lost, leaving behind these brighter materials along the floor of the valley. Bright material is also seen at the bottom of the trough (Fig. 9a) where a darker mantle appears to be eroding away to expose the underlying light-toned material. More discussion of light-toned deposits occurs in the next section.

3.5. *Light-toned layered deposits*

A light-toned layered deposit (LTLD) to the east of the fan deposit along the floor of the trough (Fig. 7) may represent another water-lain deposit, perhaps an evaporitic unit that formed when water from the valley partially filled the trough. The LTLD appears similar in morphology to the light-toned layered deposits that fill many of the troughs of Valles Marineris (Lucchitta et al., 1992; Malin and Edgett, 2000). Darker debris and dunes cover much of the LTLD, particularly on flat-lying portions (Fig. 10). The boundaries between these dark debris units and the LTLD can be very sharp, suggesting either active winds to maintain pronounced edges along the dark unconsolidated debris or a cemented dark debris unit that has been eroded by the wind. Small dark circles 10–20 m in diameter on the LTLD could be impact craters now filled with dark debris. The LTLD can be traced upwards along the adjacent northeastern wallrock. A dark mantle covers the wallrock and portions of the LTLD at this contact, so we cannot determine if the LTLD pre-dates or post-dates the wallrock.

Alternating dark and light banding in the MOC images appears to demarcate different layers, most only a few meters thick. Several layers appear much brighter than adjacent layers. The differences in brightness could be a reflection of dark debris covering some of the flat-lying layers. However, several layers appear much brighter even though they seem to have the

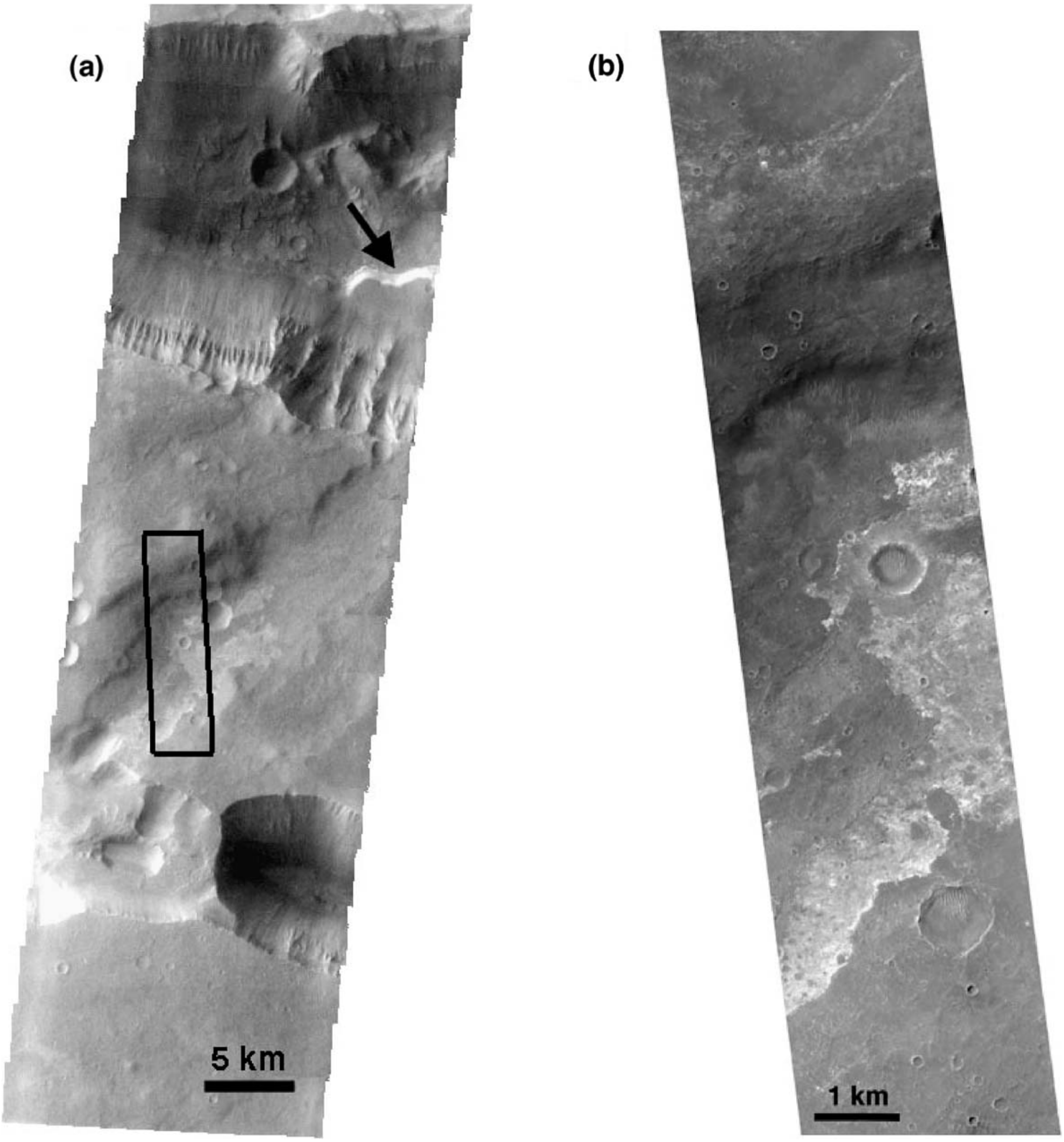


Fig. 9. Bright deposits in a possible valley and a trough to the east of the terraced fan deposit. (a) Light-toned unit in the trough (black arrow) is only visible where overlying dark debris has been eroded away along the floor. Box indicates location of (b). Portion of THEMIS VIS image V05046003. (b) Portion of MOC image E2100198 showing light-toned unit on the floor of a possible valley or topographic depression.

same slopes as darker layers above and below them, suggesting there are differences in compositions of the layers to create these brightness differences rather than just dust and debris covering.

An elongate pit crater to the east also has exposures of the LTLD along the top surfaces, but darker bedrock dominates the lower exposures in the pit (Fig. 10). The LTLD cannot be traced to the east along the pit crater but lower dark bedrock layers can still be seen to the east. This observation indicates that the LTLD is a relatively younger unit. Because the dark mantle covers much of this area, we cannot ascertain the extent of the LTLD. Formation of the pit crater after deposition of the LTLD and continued erosion along the western side of the pit has exposed and removed LTLD here. Hence, LTLD was deposited as a sedimentary unit, followed by burial underneath a dark mantle, and now is exposed where the overlying dark mantle has been stripped away by the wind.

The light-toned deposit in the trough to the east (Fig. 9a) could be a similar sedimentary unit underlying a darker mantle. Because light-toned layered deposits are seen in many locations inside Valles Marineris (e.g., Malin and Edgett, 2000), and since water fill in other locations of Valles Marineris that also have LTLD is not as obvious, we cannot uniquely tie the LTLD to any water that may have filled the trough in association with the formation of the fan deposit.

4. Discussion

We now explore several possible origins for the terraced fan deposit. These origins include alluvial fan, volcanic flow, mass

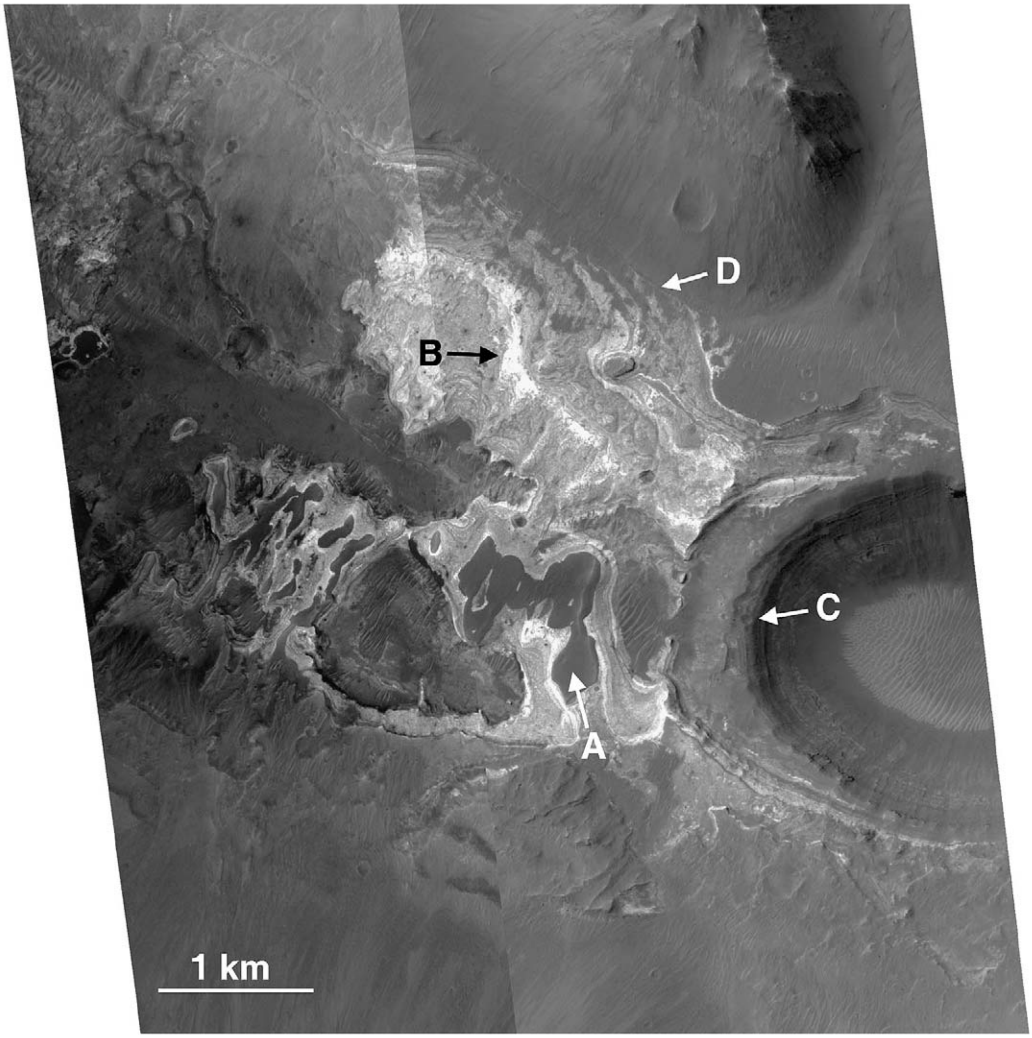


Fig. 10. Light-toned layered deposit (LTLD) located on the trough floor to the east of the terraced fan deposit. Dark debris (A) covers much of the LTLD, as does debris shed off the adjacent wallrock (D). Some of the layers appear much brighter than others (B), perhaps reflecting higher albedo material. A pit crater to the east has exposed darker layered bedrock just below the LTLD (C). Mosaic of a portion of MOC images R0200679 and E0902742.

wasting deposit, and delta. Although each origin can explain some attributes of the terraced fan, we find that one scenario best explains all of the observations. We propose that the fan deposit formed initially as a delta in a lake within the trough, and the concentric terraces formed or were enhanced later by erosion and re-distribution of fan material associated with each drop in lake level.

4.1. *Alluvial fan origin*

The terraced deposit at Coprates Catena is similar in some ways to alluvial fans on Earth, which are also fan-shaped and appear as a cone radiating away from a single point source. Unlike a terrestrial alluvial fan, however, this deposit does not emerge from the confines of a mountain but rather from a broad valley that intersects the steep walls of a trough. Nevertheless, the topographic setting is similar. Terrestrial drainage basins in the mountains have tributary channels, including the feeder channel that emerges from the highlands and is the source of material that composes the fan. Alluvial fans are steepest near the mountain front where the river emerges from the confines of the mountain at the fan head. The fans tend to be coarse-grained near their heads whereas toward their toes they are often finer-grained and better sorted. The initiation of deposition in alluvial fans is due to the increase in width, and associated reduction in velocity, once a stream reaches the end of a confining valley where high sediment loads encounter zones of reduced stream power (Bull, 1977). Fans emplaced by debris flows are poorly sorted and landforms include marginal levees, terminal lobes and trapezoidal to U-shaped channels (Costa, 1988; Ritter et al., 1995).

Many alluvial fans on Earth have well-developed systems of sinuous to anastomosing distributary channels. The lack of these braided channels on the Coprates Catena fan implies that it did not form in a similar manner, or that the channels have subsequently been buried or destroyed. The occurrence of undissected circumferential scarps precludes the possibility of any flow down the fan surface after the scarps formed, except near the top of the fan where the small fan head valley and channel are located. The fan head channel demonstrates the flow of water through the valley, which could have been involved earlier in the emplacement of the fan deposit. Alluvial fans on Earth also initiate from streams in mountain catchment channels that become more deeply confined as they flow to the mountain front. In the case of Coprates Catena, there is only one valley system leading to the fan deposit and there is no watershed of drainage catchment along mountains that feed this valley.

A survey of alluvial fans within craters from 0° to 30° S by Moore and Howard (2005) showed broad, low-gradient morphologies characteristic of fluvial fan deposits. These alluvial fans are much broader with smaller slopes than the Coprates Catena fan deposit. Additionally, there are no terraces along the fan surfaces similar to those at Coprates Catena. Thus, the terraced fan deposit at Coprates Catena must have formed by a different process, or it was modified differently (e.g., subjected to a greater amount of erosion, resulting in the terraced topography) relative to the martian alluvial fans identified by Moore and Howard (2005).

Di Achille et al. (2006) propose that the Coprates Catena terraced fan formed as an alluvial fan by a series of sheet floods that deposited material in a retreating stack of laterally coherent layers. Their scenario lacks a sound theoretical basis or empirical analog, however, and the physical processes involved in sediment transport and deposition on alluvial fans rule it out as a likely explanation for peripheral scarps or terraces. Cooke et al. (1993) note that the cone shape of a fan is the consequence of a continually changing pattern of channels and deposition sites, with each flow only encompassing a small percentage of the fan area. Hence, the radial dispersal of sediment over the entire fan surface in each flow event as proposed by Di Achille et al. (2006) is not a characteristic of terrestrial alluvial fans. Moreover, the natural irregularity of fan surfaces, a result of the different flow requirements for various size fractions of the sediment load, precludes the even distribution of sediment across the fan surface. Coarser bed material would accumulate near the fan head, and fines would settle and be deposited farther downfan. Consequently, the proposed sheet flood formation for the fan by Di Achille et al. (2006) offers no explanation for the peripheral scarps.

4.2. *Volcanic flow origin*

Although the valley could be a volcanic rille with the fan deposit representing a lava flow (e.g., Leverington and Maxwell, 2004), we do not favor this origin. There is no evidence for multiple flow lobes on the fan deposit that would be expected for a typical basaltic lava flow. The fan-like shape of the deposit is more consistent with viscous lava flows on Earth, but there is no evidence that such a higher silica lava flow would erupt on Mars. The increase in width of the valley as it nears the trough also indicates that material on the plains was eroded laterally and deposited within the trough, something not seen in volcanic rilles. The fact that the volume of the fan deposit is nearly equivalent to that of the volume of the valley from which it emanates is also more consistent with a fluvial rather than volcanic origin. In addition, the lack of a volcanic source at the beginning of the channel and valley, as well as the evidence for a sinuous channel along the fan surface do not support lava activity as the cause for the valleys, channels, and terraced fan deposit.

4.3. *Mass wasting origin*

Malin and Edgett (2003) examined several of the terraced fans on Mars and interpreted them as mass wasting deposits. They point out that they have three characteristics that distinguish them from alluvial fans: They consist of only a single lobe of material, they lack a radial pattern of conduits, and they display concentric steps. The concentric terraces could be the result of successive surges of material moving out of the valley or compressive stress following deposition of the apron (Malin and Edgett, 2003).

Although Malin and Edgett (2003) raise valid points for why these terraced fan deposits are not alluvial fans, in the case of Coprates Catena, at least, we do not favor a mass wasting formation mechanism for several reasons. Irwin et al. (2005) argue that such a large number of regularly retreating debris flows would be extraordinary without some base level control within the basins, and individual debris flow deposits are often more elongated than these scarp-bounded shapes. Mass wasting is a common phenomenon along the walls of Valles Marineris (Lucchitta, 1979; McEwen, 1989; Quantin et al., 2004), but the resulting landslides do not share the morphology seen in this fan deposit. Quantin et al. (2004) observe that all Valles Marineris landslides of various ages have the same morphology, which includes longitudinal grooves on a large, relatively thin debris apron. Typical landslides in Valles Marineris also have an uphill circular scarp that would support a mass wasting origin produced by collapse and subsequent downslope movement of material. There is no similar scarp, other than the highly elongated valley itself at Coprates Catena. Hence, the process that emplaced this terraced fan, as well as those elsewhere on Mars, must be different from the mass wasting that produced the typical Valles Marineris landslides. The clear association between the channel, valley, and fan deposit at Coprates Catena also indicates that material was transported along the valley and deposited on the trough floor once the valley entered into the trough.

4.4. *Delta origin*

Ori et al. (2000) proposed that the terraces in a lobate fan deposit in the Memnonia region could be shorelines from a standing body of water. Malin and Edgett (2003) objected to this interpretation on the basis that there is no evidence for shorelines on any of the wallrock in the trough. However, the steep unstable slopes of the wallrock are subject to collapse and talus formation, which would make it difficult to preserve these same shoreline terraces. In addition, the fan deposit is composed of unconsolidated debris that would consequently be more susceptible to erosion by waves than the harder bedrock in the wallrock. Another concern with forming the terraces by water erosion is that Mars has no significant tides, although winds rather than tides could produce wave motion. Bodies of water were likely to have been ice covered under contemporary climatic conditions (e.g., Squyres and Kasting, 1994; Carr, 1996). Kraal et al. (2006) proposed that ice cover on a lake could possibly explain scarps and terraces on martian features rather than erosion by waves. A recent discovery of scarp-bounded benches in Gorgonum Chaos led Howard and Moore (2004) to postulate several origins for the benches, but with a preferred hypothesis of formation in an ancient ice-covered lake by deformation of soft sediments.

In the case of Coprates Catena, the trough could have once had water contained within it, fed by the same valley that initiated the fan deposit. If we attribute the terraces to erosion along past shorelines of a lake inside the trough, then the maximum terrace height on the fan should correspond to the water level within this lake. The lake could have been higher than the top terrace on the fan, but the lack of preservation of shorelines along the wallrock would prevent us from seeing the maximum height of this level. From the MOLA DEM, the top of the fan head is approximately 1800 m above the floor of the trough. The volume of a lake inside the trough would be approximately 270 km^3 if it filled to the top of the fan and the mouth of the valley entering the trough. For comparison, Fassett and Head (2005) estimate a volume of 350 km^3 for the amount of water that filled the Nili Fossae crater where they have identified distributary fans.

4.5. Proposed formation model of the terraced fan deposit

We favor a scenario that combines several events to form the Coprates Catena terraced fan deposit. Initially, volcanic heating associated with eruption of lavas on the plains or magmatic intrusions into the plains to the south could have melted ice on or near the surface. We do not favor the unnamed putative volcano as the specific heat source for this melting because lava flows that erupted from the volcano do not appear to have traveled this far to have heated and melted any ice. Additionally, the cratered surface of the volcano implies that it is significantly older than its surroundings. The water released from this melting pooled together to form the channel and valley by downcutting into the plains, with flow towards the north. Upon intersection with the trough, water incised the wallrock at this steep intersection and also began to fill the floor of the trough. As the resistant upper layers visible in the contributing valley became eroded away and the knickpoint migrated upstream, less resistant material was exposed, eroded, and transported downstream to be deposited as part of the fan.

As sediment and water discharge continued, the water level rose and the site of deposition retreated headward. The terraces along the fan, consequently, could represent stages where the deposition of material was less than the previous episode, perhaps due to declining stream power as the contributing valley's discharge and gradient declines, causing successively smaller deposits on the prior fan surface. The concentric scarps would be very difficult to produce unless they were controlled by a rising water level in the trough, however. This increase in base level during deposition might create a stacked fan-delta (Irwin et al., 2005). This scenario also can explain why deposition occurred at the mouth of the valley, even though the slope along the fan is twice that of the contributing valley just before it enters the trough. If water were present in the trough to a height above or equal to that of the fan surface, then deposition would be possible along the steeper gradient of the wallrock seen downstream of the contributing valley. One concern with this scenario, however, is that suspended load from each successive delta sequence should settle onto the earlier deposits without preserving the pronounced terrace. In addition, we might expect the shape of the deposit to look more like the distributary deltas identified elsewhere on Mars (Malin and Edgett, 2003; Moore et al., 2003; Fassett and Head, 2005).

Post-modification of the stacked deltas by a receding lake level could explain both the fan-shape and the terraces. If the fan deposit was emplaced subaqueously and the amount of water in the trough diminished both because water flowing through the valley decreased with time and also as water in the trough sublimated or drained, then the lake level would lower. With each drop in lake level, the fan surface at the same height of the current lake level would experience erosion and re-distribution of material at this height by wave and current movements in the water, thus producing the terraces and rounded shape of the fan compared to the more irregular shapes of the non-terraced fan deposits seen at Nili Fossae and Holden Crater. A similar analog exists on Earth for the debris flow and sheet flood fans of Pagodroma gorge in Antarctica where seasonal thaw activates debris flows which enter into a tidal lake (Webb and Fielding, 1999). The terminus of these fans is marked by a sharp break in slope and wide sandy beach along which the fan sediment is reworked between high and low tide. If the lake existed under current climate conditions of Mars, then it was likely covered by ice. Erosion and redistribution of material just below the ice-cover could also explain the terraces on the fan, as terrestrial glacial lakes are documented to have produced shorelines (Gilbert and Desloges, 2005).

Another important issue is why sediment would be deposited on a fan that is steeper than the contributing valley, as convex breaks in slope are not typical and should lead to entrenchment of the fan head while the fan is forming. Given the limited resolution of available topographic data, we are not certain whether the steep fan gradient represents more the slope at which deposition occurred or the cumulative effect of multiple near-vertical scarps. If the scarps represent a rising lacustrine base level during deposition or subsequent shore erosion, then the issue of how gradient could increase so abruptly without causing fan-head entrenchment is circumvented. Upon reaching a shoreline, Blair and McPherson (1994) note that alluvial fans can transform into Gilbert-deltas and also be significantly steepened due to aggradation higher on the fan and from erosion by waves or longshore currents.

When the discharge declined from the contributing valley, there was no longer any deposition on the fan. Instead, the final remnants of water flow incised the fan head to produce the valley and channel on the fan surface to the east. The elevation of this fan head valley and channel system may reflect the height of water within the trough at the time of their formation, with surface flow carving the valley and channel above the water level, but ponded water preventing the channel and valley from developing below this height. We determine a height of 1.5 km above the lowest point on the floor as the top of this lake level when the channel and valley incised the upper portion of the fan. As water in the trough sublimed or evaporated away, the light-toned layered deposits could have formed along the floor where pools of water collected and concentrated minerals.

The two postulated valleys to the east may have also originated by volcanic heating of near-surface ice, though the water volume may have been significantly less and we find no fan deposit associated with them. Light-toned units seen along the floor of one of these valleys, along an older crater rim, and in a trough to the east may also be evidence for past water activity in this region. The lack of tributaries associated with these valleys suggests that they did not form by precipitation, as has been proposed for nearby valley networks in Melas Chasma (Quantin et al., 2005).

Thus far, we have seen only one other terraced fan deposit in the Valles Marineris region, a 3.3 km long fan inside an impact crater at 9.8° S, 306.6° E located at the end of a small valley near Valles Marineris. The paucity of these terraced fans could be attributed to the constraints required to form them, such as a nearby volcanic source and ice deposits, a steep drop from the plains into a trough or crater, accumulation of a standing body of water in a topographic low, and collapse/removal of upstream material due to erosion from the water movement. Unless all these conditions are met, the terraced fan deposits will not form. The lack of channels and apparent knickpoints associated with the other terraced fan deposits on Mars suggests that they probably did not form by the same scenario we have described for the Coprates Catena fan deposit. Instead, each terraced fan deposit may have slightly varying conditions during its emplacement, though each appears to result in a similar overall morphology.

5. Conclusions

We propose that the terraced fan in Coprates Catena initially formed as a delta in a lake that partially filled the trough. The lake may have been ice-covered, assuming it formed under current climate conditions. Water that fed the lake and formed the contributing valley and channel likely resulted from volcanism melting surface or subsurface ice in the plains to the south. Once the water in the valley reached the edge of the trough, erosion of material downstream of a knickpoint supplied most of the material that was deposited to form the fan. The concentric terraces on the fan most likely formed by shoreline erosion or ice-cover as lake levels dropped with time. The fan shape may have partially resulted from erosion and redistribution of material in the delta by water currents in the lake. A light-toned layered deposit on the eastern floor of the trough could represent minerals deposited as evaporates during the terminal stage of the lake. Similar light-toned deposits and valleys to the east suggest that this region experienced multiple episodes of volcanic heating and melting of near-surface volatiles during the Hesperian Period.

Acknowledgments

We thank Caleb Fassett and an anonymous reviewer for their valuable comments. We also thank John Grant for thoughtful reviews of an earlier version of the manuscript. Thanks to NASA/JPL/Malin Space Science Systems for the MOC images, and NASA/JPL/Arizona State University for the THEMIS images. This work was supported by NASA MDAP Grant NNG04GO56G. This manuscript is PSI Contribution 399.

References

Bhattacharya, J.P., Payenberg, T.H.D., Lang, S.C., Bourke, M.C., 2005. Dynamic river channel suggests a long-lived Noachian crater lake on Mars. Geophys. Res. Lett. 32, doi:10.1029/2005GL022747. L10201.

Beyer, R.A., McEwen, A.S., 2005. Layering stratigraphy of eastern Coprates and northern Capri Chasmata, Mars. Icarus 179, 1–23.

Blair, T.C., McPherson, J.G., 1994. Alluvial fan processes and forms. In: Abrahams, A.D., Parsons, A.J. (Eds.), Geomorphology of Desert Environments. Chapman & Hall, London, pp. 354–402.

Bull, W.B., 1977. The alluvial fan environment. Prog. Phys. Geogr. 1, 222–270.

Cabrol, N.A., Grin, E.A., 2001. The evolution of lacustrine environments on Mars: Is Mars only hydrologically dormant? Icarus 149, 291–328.

Carr, M.H., 1996. Water on Mars. Oxford Univ. Press, New York.

Cooke, R., Warren, A., Goudie, A., 1993. Desert Geomorphology. UCL Press, London.

Costa, J.E., 1988. Rheologic, geomorphic and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley & Sons, New York, pp. 113–122.

Crown, D.A., Greeley, R., 1993. Volcanic geology of Hadriaca Patera and the eastern Hellas region of Mars. J. Geophys. Res. 98, 3431–3451.

Di Achille, G., Ori, G.G., Reiss, D., Hauber, E., Gwinner, K., Michael, G., Neukum, G., 2006. A steep fan at Coprates Catena, Valles Marineris, Mars, as seen by HRSC data. Geophys. Res. Lett. 33, doi:10.1029/2005GL025435. L07204.

Fassett, C.I., Head III, J.W., 2005. Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in Nili Fossae region. Geophys. Res. Lett. 32, doi:10.1029/2005GL023456. L14201.

Gilbert, R., Desloges, J.R., 2005. The record of Glacial Lake Champagne in Kusawa Lake, southwestern Yukon Territory. Can. J. Earth Sci. 42, 2127–2140.

Greeley, R., Spudis, P.D., 1981. Volcanism on Mars. Rev. Geophys. Space Phys. 19, 13–41.

Howard, A.D., Moore, J.M., 2004. Scarp-bounded benches in Gorgonum Chaos, Mars: Formed beneath an ice-covered lake? Geophys. Res. Lett. 31, doi:10.1029/2003GL018925. L01702.

Irwin, R.P., Howard, A.D., Craddock, R.A., Moore, J.M., 2005. An intense terminal epoch of widespread fluvial activity on early Mars. 2. Increased runoff and paleolake development. J. Geophys. Res. 110, doi:10.1029/2005JE002460. E12S15.

Kraal, E.R., Asphaug, E., Moore, J.M., Lorenz, R.D., 2006. Quantitative geomorphic modeling of martian bedrock shorelines. J. Geophys. Res. 111, doi:10.1029/2005JE002567. E03001.

Leverington, D.W., Maxwell, T.A., 2004. An igneous origin for features of a candidate crater-lake system in western Memnonia, Mars. J. Geophys. Res. 109, doi:10.1029/2004JE002237. E06006.

Lucchitta, B.K., 1979. Landslides in Valles Marineris, Mars. J. Geophys. Res. 84, 8097–8113.

Lucchitta, B.K., Balser, R.A., Bertolini, L.M., 1990. Valles Marineris, Mars: Are pit chains formed by erosion and troughs by tectonism? Lunar Planet. Sci. XXI, 722–732. Abstract.

Lucchitta, B.K., McEwen, A.S., Clow, G.D., Geissler, P.E., Singer, R.B., Schultz, R.A., Squyres, S.W., 1992. The canyon system on Mars. In: Kieffer, H.H., Jakosky, B.M., Snyder, C.W., Matthews, M.S. (Eds.), Mars. Univ. of Arizona Press, Tucson, pp. 453–492.

Malin, M.C., Edgett, K.S., 2000. Sedimentary rocks of early Mars. Science 290, 1927–1937.

Malin, M.C., Edgett, K.S., 2003. Evidence for persistent flow and aqueous sedimentation on early Mars. Science 302, 1931–1934.

McEwen, A.S., 1989. Mobility of large rock avalanches: Evidence from Valles Marineris, Mars. Geology 17, 1111–1114.

McEwen, A.S., Malin, M.C., Carr, M.H., Hartmann, W.K., 1999. Voluminous volcanism on early Mars revealed in Valles Marineris. Nature 397, 584–586.

Mege, D., Cook, A.C., Garel, E., Lagabrielle, Y., Cormier, M.H., 2003. Volcanic rifting at martian grabens. J. Geophys. Res. 108 (E5), doi:10.1029/2002JE001852. 5044.

Moore, J.M., Howard, A.D., 2005. Large alluvial fans on Mars. J. Geophys. Res. 110, doi:10.1029/2004JE002352. E04005.

Moore, J.M., Howard, A.D., Dietrich, W.E., Schenk, P.M., 2003. Martian layered fluvial deposits: Implications for Noachian climate scenarios. Geophys. Res. Lett. 30 (24), doi:10.1029/2003GL019002. 2292.

Ori, G.G., Marinangeli, L., Baliva, A., 2000. Terraces and gilbert-type deltas in crater lakes in Ismenius Lacus and Memnonia (Mars). J. Geophys. Res. 105, 17629–17641.

Plescia, J.B., Saunders, R.S., 1979. The chronology of the martian volcanoes. Proc. Lunar Sci. Conf. 10, 2841–2859.

Quantin, C., Allemand, P., Mangold, N., Delacourt, C., 2004. Ages of Valles Marineris (Mars) landslides and implications for canyon history. Icarus 172, 555–572.

Quantin, C., Allemand, P., Mangold, N., Dromart, G., Delacourt, C., 2005. Fluvial and lacustrine activity on layered deposits in Melas Chasma, Valles Marineris, Mars. J. Geophys. Res. 110, doi:10.1029/2005JE002440. E12S19.

Ritter, D.F., Kochel, R.C., Miller, J.R., 1995. Process Geomorphology, third ed. McGraw–Hill, Boston, MA.

Saunders, R.S., Roth, L.E., Downs, G.S., Schubert, G., 1980. Early volcanic–tectonic province: Coprates region of Mars. In: Reports of Planetary Geology Program, 1979–1980: U.S. National Aeronautics and Space Administration Technical Memorandum 81776, pp. 74–75.

Schultz, R.A., 1989. Do pit-crater chains grow up to be Valles Marineris canyons? In: Watters T.R., Golombek M.P. (Eds.), MEVTV Workshop on Tectonic Features on Mars. LPI Tech. Report 89-06, pp. 47–48 (abstract).

Smith, D.E., Zuber, M.T., Frey, H.V., Garvin, J.B., Head, J.W., Muhleman, D.O., Pettengill, G.H., Phillips, R.J., Solomon, S.C., Zwally, J.J., Banerdt, W.B., Duxbury, T.C., Golombek, M.P., Lemoine, F.G., Neumann, G.A., Rowlands, D.D., Aharonson, O., Ford, P.G., Ivanov, A.B., Johnson, C.L., McGovern, P.J., Abshire, J.B., Afzal, R.S., Sun, X., 2001. Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars. J. Geophys. Res. 106, 23689–23722.

Squyres, S.W., Kasting, J.F., 1994. Early Mars: How warm and how wet? Science 265, 744–749.

Webb, J.A., Fielding, C.R., 1999. Debris flow and sheetflood fans of the northern Prince Charles Mountains, east Antarctica. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. Wiley & Sons, Chichester, pp. 317–341.