

Glacial deposits on the rim of a Hesperian-Amazonian outflow channel source trough: Mangala Valles, Mars

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Received 19 April 2004; accepted 22 April 2004; published 21 May 2004.

[1] Mangala Valles, located in tropical regions of Mars, is interpreted to have formed by dike-induced cracking of the cryosphere to produce a linear graben and catastrophic release of groundwater sequestered under hydrostatic pressure. Outpouring of water and downcutting led to erosion and widening of the graben to produce a trough. Patterns of ridges and lobes along the outer rims of the trough are interpreted to have formed primarily by local accumulations of snow and ice on the graben rim (derived from exposed ponded groundwater in the graben), and glacial-like outward flow of ice lobes resulting in development of moraines and tills along the north and south rims of the trough. These observations and interpretations support the concept that the climate of Mars was a hyper-arid cold polar-like desert similar to today in the Late Hesperian-Early Amazonian period. *INDEX TERMS*: 5400 Planetology: Solid Surface Planets; 5407 Planetology: Solid Surface Planets: Atmospheres—evolution; 5416 Planetology: Solid Surface Planets: Glaciation; 6225 Planetology: Solar System Objects: Mars. **Citation**: Head, J. W., III, D. R. Marchant, and G. J. Ghatan (2004), Glacial deposits on the rim of a Hesperian-Amazonian outflow channel source trough: Mangala Valles, Mars, *Geophys. Res. Lett.*, *31*, L10701, doi:10.1029/2004GL020294.

1. Introduction

[2] What were the climate conditions like on Mars at lower latitudes earlier in its history in the Late Hesperian-Early Amazonian several billion years ago? We approach this question by examining Mangala Valles, the result of massive water outflow that emanated from the subsurface through graben-related fractures associated with the Memnonia Fossae system, and drained downslope northward into the northern lowlands over a distance of ~900 km [Tanaka and Chapman, 1990; Zimbelman *et al.*, 1992; Ghatan *et al.*, 2004]. The source graben is plausibly interpreted to be the result of near-surface deformation caused by large dikes radiating from the Tharsis region [Wilson and Head, 2002]. On the basis of the amount of water estimated to have been released from the subsurface in the Mangala floods, large quantities of water must have

been sequestered underground under hydrostatic pressure [Tanaka and Chapman, 1990; Zimbelman *et al.*, 1992]. The most likely candidate for a hydrostatic seal is a globally continuous upper crustal cryosphere [Clifford, 1993]. The presence of such a cryospheric seal implies that at the time of the Mangala outflow events, Mars was a cold polar-like desert, much like conditions on the surface today. Emplacement of the dike and formation of the graben appears to have cracked the cryosphere [e.g., Head *et al.*, 2003] and released extensive groundwater into the graben, overtopping it locally and rapidly downcutting hundreds of meters to form an egress channel notch for the water outflow and drainage that formed Mangala Valles [Ghatan *et al.*, 2004]. Effusion of water into a hyper-arid cold polar-like desert climate such as observed presently on Mars would result in rapid freezing of a surface boundary layer at rates dependent on flux and turbulence. Standing bodies of water would freeze solid and sublimate in geologically short periods of time [e.g., Kreslavsky and Head, 2002]. Recent acquisition of data from Mars Global Surveyor (MGS) (MOC images and MOLA altimetry) and Mars Odyssey (THEMIS images) has provided sufficient resolution to examine details of the graben floor and margins and to test predictions of water emplacement models and assess climate conditions at the time of formation of Mangala Valles.

2. Description and Interpretation of Trough Rim Deposits

[3] Mangala Valles (Figure 1) emerges from one of the Memnonia Fossae graben at a localized egress notch (−18.2, 210.7) in the northern flank of the graben. This segment of the graben is approximately 220 km long, beginning at its proximal eastern end (toward Tharsis) on the flank of a major ridge and becoming diffuse in the cratered uplands to the west along the distal portion. The actual graben itself is about 2 km wide and tens to hundreds of meters deep, but in this region has been enlarged to a trough and the original graben scarps and walls are visible only further along strike. MOLA data (Figure 2) show that the trough in this region is generally ~7 km wide, and ranges up to ~1.5 km deep. The egress notch forms at a portion of the trough characterized by an en-echelon left-lateral offset, a place where the trough widens to 10–15 km.

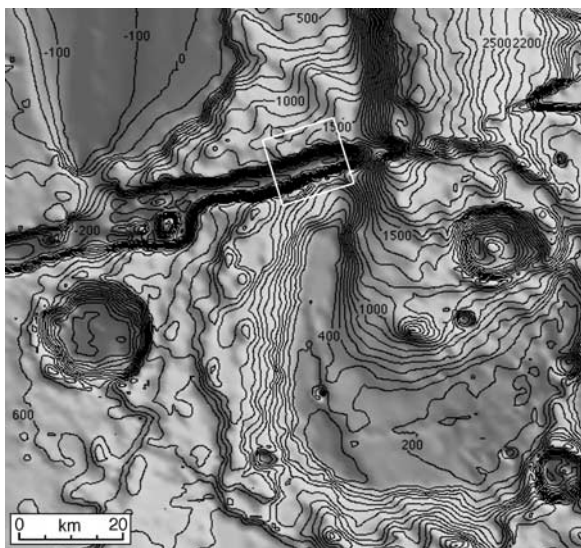


Figure 1. Topography and major features of Memnonia Fossae (trough across top) and Mangala Valles source region (U-shaped depression and notch in upper left). Notch is located at -18.2 latitude and 210.7 longitude. Contour interval is 100 m and North is at the top. Square shows location of Figure 3. See color version of this figure in the HTML.

THEMIS data (Figure 3) provide insight into the nature of the deposits forming along the rim of the trough.

[4] Analysis of THEMIS data of the southern rim of the proximal part of the erosionally enlarged graben (trough) east of the egress notch reveals two major lobate deposits (Figures 3a–3b), each extending approximately 10 – 11 km downslope from the southern margin of the trough. The downslope ends of these features are ~ 2 km wide and distinctly lobate, with steep margins and concentric ridge-like features internal to the lobes. The ridges within the deposit are typically 50 – 150 m wide and range up to ~ 2 km in length, with ridge-to-ridge spacing of 200 – 250 m. The margins of the lobate features broaden as they extend upslope back toward the trough rim, and the concentric ridge patterns broaden outward, becoming parallel to the trough ridge crest and apparently interconnecting between lobes. The distal (downslope) parts of the lobes appear flow-like in appearance and are clearly extending down into and occupying local low-lying regions.

[5] The intermediate to proximal (headward) parts of these features are more complex. Individual large ridges can be traced generally parallel to the trough margin and are well developed in a 2 – 4 km wide band that is tangential to the trough rim. Numerous prominent ridges are orthogonal to these ridge sets and are generally correlated with the positions of the distal lobes. Superposition relationships suggest that the lobes post-date (or modify) the parallel ridge sets. Toward the trough rim, the ridges become less distinct to patchy, particularly along the western half of Figure 3a, and sometimes break up into a series of elongated or isolated knobs. Areas along the trough rim that appear topographically high (Figure 3b) show the least evidence for ridges and knobs, which tend to be concentrated in trough rim lows. The extreme head-

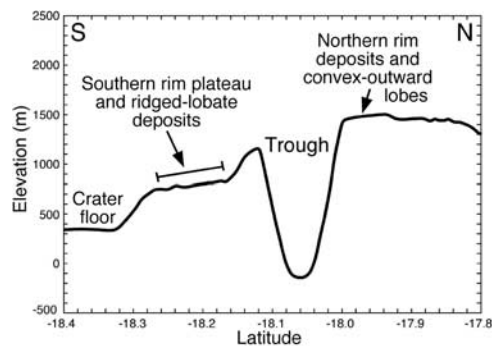


Figure 2. MOLA profile (section of 13451) across the trough and margins. Annotations refer to features seen in Figure 3. Location in eastern part of square in Figure 1.

ward parts of the lobes appear to emanate from distinctive lows in the rim crest (Figures 3a–3b).

[6] The underlying topography of the broad trough rim provides insight into the distribution of these features (Figure 3b). Adjacent to the rim is a broad, but hummocky plateau about 5 – 8 km wide, which is part of the northern section of the 80 km diameter impact crater cut by the graben (Figure 1). The plateau, which may be a very degraded terrace of the crater wall, drops downward from its edge some 500 m toward the crater floor (Figure 2). The parallel linear ridges of the deposit show a preferred orientation parallel to the trough rim crest in the vicinity of the edge of the plateau, but then converge and tend to point downslope as they near the two low points in the plateau margins (see arrows in Figure 3b).

[7] The following characteristics describe the features and deposits on the southern rim (Figures 3a–3b): 1) a relatively continuous deposit of ridges and knobs superposed on underlying terrain at the edge of the trough rim crest, 2) patterns of ridges and knobs that suggest flow

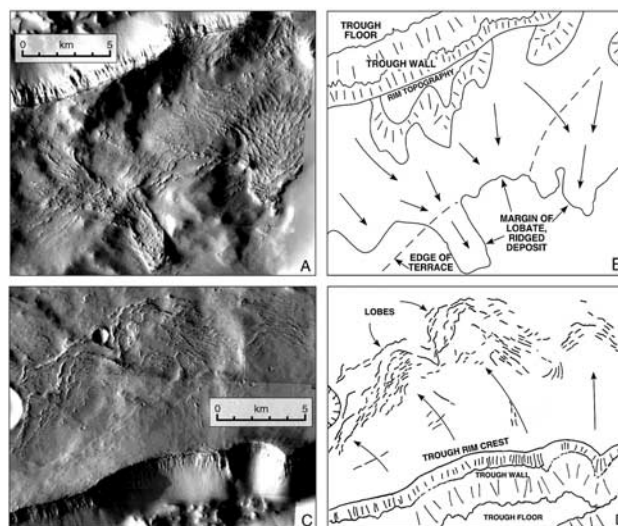


Figure 3. Ridged and lobate features on the trough rim. (a) Southern rim and ridges and lobes. (b) Explanatory sketch map. (c) Northern rim convex outward lobes. (d) Explanatory sketch map. Portions of THEMIS image V06597003.

downslope away from the rim and then focused into lows, 3) discontinuous marginal contacts and lack of thick internal deposits comparable to the height of the ridges.

[8] The northern rim of the trough, which typically stands a few hundred meters above the southern rim (Figure 2) in the study region, represents part of the degraded rim area of the large 80 km diameter crater into which the graben cuts (Figure 1), and generally appears flatter and smoother than the southern rim. Examination of the features and structures on the northern rim reveals a host of ridges similar to those seen on the southern rim, but arrayed somewhat differently (Figures 3c–3d). The ridges are approximately the same scale, but in contrast to the distinctive parallel/lobate patterns seen on the southern rim, these ridges are arrayed in a pattern of 3–4 broad, convex-outward arcuate lobes in a band 3–5 km wide, located about 3 km from the rim. Each convex-outward lobe is about 4–5 km wide, and the 3 km wide region between this band of arcuate lobes and the trough rim is relatively flat and smooth, containing only a few subdued ridges and knobs.

[9] The following characteristics describe the features and deposits on the northern rim (Figures 3c–3d): 1) a band of arcuate, convex-outward ridges and knobs superposed on underlying terrain, 2) a smooth region between this band and the edge of the trough rim crest, 3) patterns of arcuate ridges out away from the trough, suggesting outward flow, and 4) generally symmetric marginal ridges suggesting that the ridges are not currently forming the margin of a thick flow, such as a lava flow.

[10] The geological environment of the graben-trough system provides candidates for interpreting these deposits. Dike-emplacment and associated volcanism, tectonic deformation, landsliding, and associated cracking of the cryosphere and catastrophic release of sequestered groundwater all may be involved. Short, stubby volcanic flows are seen adjacent to some dike-related outflow channels [e.g., *Head et al.*, 2003] and share some of the lobate morphology seen on the southern rim, but do not have the same scale of distinctive ridges. Such distinctive ridges could be related to a more viscous magma or anomalous conditions such as sub-ice emplacement and chilling. However, the lack of a thick deposit interior to the outer ridges and the draping of ridges over relatively high subjacent topography both argue against a lava flow mechanism for formation. Landslides offer a possible alternative explanation, with over-steepened graben slopes causing failure and lateral movement. The very shallow slopes and lack of obvious source regions do not provide strong support for this option. Furthermore, an examination of THEMIS images for similar features along other parts of the Tharsis-radial graben failed to reveal any additional examples, suggesting that their origin is related to the outpouring of water in this region.

[11] Another option involves groundwater erupting from the subsurface to flood the graben and to produce ice deposits on the trough rim. In this scenario, the deposits could be related to flow of ice on the rims, the formation of ridges and knobs as moraines from residual ice and sediment, and the ultimate sublimation and loss of the ice, leaving behind an array of tills and moraines. This interpretation is favored by the draping of the ridges over a variety of subjacent topography regardless of slope, the broad control of the flow patterns (lobes) by prominent

topographic depressions, and the lack of thick inner deposits, consistent with the idea that material has been lost by sublimation.

[12] In this scenario, ice accumulating at the trough rim crests flows out onto the narrow plateau, and then on the southern rim funnels into the depressions at the edge of the plateau to form lobes extending down toward the crater floor. Erosion of the substrate at the trough rim and atmospheric dust deposition on the ice produces sediment-rich ice; sediment is then concentrated at the margins of the deposit by flow and sublimation, and multiple parallel ridges and knobs are created as the deposit retreats and eventually the ice disappears. This scenario is also favored by the presence of a central depression in the western lobe, which is typical of remnant rock glacier lobes and implies that material has melted or sublimed from an ice-rich convex-upward core [*Martin and Whalley*, 1987].

[13] We interpret the arcuate sets of ridges on the northern rim to be moraines deposited from ice that advanced from the margins of the trough and then retreated episodically, forming the bands of debris. Subsequent sublimation of the ice-rich deposits along the trough rim left a thin till deposit between the band of moraines and the rim, smoothing the underlying topography.

[14] Additional examples of similar sinuous and arcuate ridges and families of ridges are observed locally along the northern and southern rim of the trough to the west. In the THEMIS image of the area just to the west (V06235003), ridges similar to the type seen in Figure 3c are observed on both the north and south rims. Although the individual ridges are often not as well developed or continuous, convex outward lobate patterns are observed and are located in a band about 5–10 km wide adjacent to the trough rim crests. In both locations, these ridges often cross over local topography, but extend as lobes into local low-lying regions, supporting a glacial origin for their formation and arguing against formation by gelifluction and flow of subsurface ground ice. In the THEMIS image of the area covering the trough notch (V04762003), ridges similar to the type seen in Figure 3c are observed in a band extending for a distance of about 5 km adjacent to and generally paralleling the south trough rim. Ridges are not observed along the trough west of the notch.

3. Discussion and Conclusions

[15] The observations of families of sinuous, generally symmetric ridges, convex outward from the margins of the trough and generally crossing topographic contours, but locally arrayed in distinctly lobate forms where underlying topography is pronounced, supports a glacier-like flow origin, rather than an origin as lava flows, landslides, or classic gelifluction lobes. A glacier-like flow origin is further supported by the lack of extensive internal topography that should be typical of a lava flow and most gelifluction lobes [e.g., *Marchant and Denton*, 1996], and by the convex downward morphology of one distinctive lobe (Figures 3a–3b), both suggesting that the flow medium was ice that subsequently sublimated.

[16] The morphology of the ridges and lobes shows distinctive similarities to terrestrial moraines and rock

glaciers respectively. *Boulton and Eyles* [1979] and *Sharp* [1984] describe moraines formed at the margins of glaciers in several different environments that show morphologies and patterns very similar to those seen in Figure 3 (see also Figures 11–49b and 11–51 in *Benn and Evans* [1998]). *Martin and Whalley* [1987] describe patterns and topography similar to those seen in the lobes in Figure 3 in glacially-derived ice-cored rock glaciers in numerous terrestrial environments.

[17] How did the ice responsible for these features originate and accumulate? Among the candidates are: 1) local water overflow and freezing, 2) marginal accumulation of water spatter and snow, 3) sublimation of an ice cover in the graben and local redeposition on the rim, 4) rise of a surface plug of ice on top of a water-filled graben, marginal grounding, and glacial-like flow into the surrounding regions, or 5) a combination of the above factors. The new high-resolution data reveal no evidence of closely associated channels, gullies, or valleys immediately adjacent to these deposits that might indicate that overtopping water flow was the major factor.

[18] Upward movement of an ice cover due to rising water level could form grounded ice dams along the rim crests of the trough, and cause flow of ice out onto the rims. This scenario is similar to the deposition of Late Wisconsin Ross Sea drift along the Scott Coast of Antarctica. In this case, the floating Ross ice shelf thickened, grounded, and advanced westward into the low-lying valleys fronting the Royal Society Range, depositing lobate tongues of drift [*Denton and Marchant*, 2000]. Another analog from the Antarctic Dry Valleys is found where outlet glaciers, confined to narrow valleys, thicken sufficiently to enable lateral flow into adjacent high-elevation hanging valleys, as abundantly documented in Wright and Arena Valleys. This process has produced a suite of distinctive outward-facing lobate moraines and drift sheets [*Marchant et al.*, 1993, 1994] that are morphologically similar to the trough-rim-margin deposits (Figure 3). In the case of these deposits (Figure 3), however, the presence of lobes on both rims despite the several hundred meter difference in rim height makes this simple explanation unlikely, as the overflow would be focused almost solely on the southern rim because of its much lower elevation.

[19] Marginal accumulation of water spatter and snow, and sublimation of an ice cover in the trough and local redeposition on the rim, are both plausible processes of ice emplacement. As the graben floods and the water boils and then freezes at the top, water vapor in this non-equilibrium environment will be enhanced in the atmosphere in the vicinity of the graben and will immediately condense onto adjacent cold traps, the cold surface of the graben rim. Further deformation and modification of the growing icy surface as the water rises and floods the graben continues to maintain this non-equilibrium environment as the deforming surface exposes relatively warm water to the ambient atmosphere. As warmer water sublimates and is rapidly redeposited on the rim, it would accumulate rapidly and at temperatures closer to the melting point of ice such that it would be amenable to flow to produce the glacial-like lobes. This process would continue until the ice cover in the graben reached a sufficient thickness so that no further

water was exposed, and ultimately this surface would reach equilibrium conditions.

[20] In summary, when water flowed into the trough, the surface of the water would certainly begin to undergo freezing if the climate was similar to the hyper-arid cold polar-like desert conditions of today. These conditions would rapidly produce an extensive local source of ice. Evaporating and sublimating warm water would be redeposited locally on the nearest cold traps, the adjacent graben rims. During this period, the hydrostatic head of groundwater flowing into the trough from below would cause the water level to rise and the ice cover to disrupt, constantly exposing warm water to the surface. This mechanism would cause snow and ice to accumulate on the rim crests and to flow out into the surrounding lows. Lowering of the water and ice level in the trough, and retreat and wasting of the ice ultimately produced the moraine and till deposits that are observed today.

[21] In conclusion, we interpret the presence of patterns of ridges and lobes along the margins of the Mangala Valles source trough to be formed by glacial-like flow primarily related to the deposition of snow and ice from the exposed water in the trough, its glacier-like movement, and its ultimate sublimation to form moraines and tills. The Mangala Valles source region is located in tropical regions of Mars. These observations and interpretations support the concept that the climate of Mars was a hyper-arid cold polar-like desert similar to today earlier in the Late Hesperian-Early Amazonian period when Mangala Valles formed several billion years ago.

[22] **Acknowledgments.** We acknowledge helpful discussions with L. Wilson, M. Kreslavsky, H. Leask, K. Mitchell, D. Shean, C. Fassett, and S. Pratt. Thanks are extended to Anne Côté and James Dickson for help in manuscript preparation.

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