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Evidence for remnants of ancient ice-rich deposits: Mangala Valles outflow channel, Mars

Joseph S. Levy and James W. Head

Department of Geological Sciences, Brown University, Providence, RI 02912, USA

ABSTRACT

High-resolution spacecraft data reveal the presence of a distinctive unit on the upper reaches of the floor of Mangala Valles, an ancient outflow channel on Mars. In contrast to abundant evidence for scour, intense erosion, and hydrodynamic shaping typical of the floors and margins of Mangala and other outflow channels, this unit is smooth-surfaced, has cuspate margins, is superposed on the scoured valley floor, and is extensively pitted. We interpret this unit to be the sublimation lag deposit derived from an ice thermal boundary layer on the aqueous flood that formed the outflow channel system, and the remnant of floodwaters trapped in channel lows. This interpretation further supports the likelihood that climate conditions at the time of emplacement were similar to the hyper-arid cold desert conditions of today. Frozen floodwaters from the ancient martian subsurface could still be preserved in these deposits, representing attractive and accessible exobiological exploration objectives.

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Introduction

Outflow channels represent one of the most dramatic manifestations of the presence, during the Late Hesperian-Amazonian periods, of huge quantities of liquid water on the surface of Mars. Features associated with outflow channels show evidence for catastrophic water release from the subsurface, extensive overland flow and erosion, ponding in low-lying regions and ultimate return to other water reservoirs (e.g. Baker *et al.*, 1991; Carr, 1996; Kreslavsky and Head, 2002). The fate of the water released and emplaced on the surface in these events has always been a matter of controversy (e.g. Carr, 1996) and the nature of such groundwater and its relation to potential exobiological environments has been of extreme interest (e.g. McKay and Stoker, 1989; McKay and Davis, 1991).

High-resolution images from MGS and Odyssey reveal an unusual unit on the floor of the Mangala Valles outflow channel (Figs 1–7). In contrast to abundant terrain showing scour and hydrodynamic shaping typical of the floors and margins of Mangala Valles and other outflow channels (e.g. Tanaka and Chapman, 1990; Zimbelman *et al.*, 1992, 1994; Craddock and Greeley, 1994; Ghatan *et al.*, 2005), this unit (Fig. 3) is smooth-surfaced, has arcuate and cuspate margins, and has a host of unusual surface features including round pits and ring structures often containing huge angular blocks (Fig. 7). We assess several possible origins for this unit and the associated features, and conclude that the most plausible explanation is an ice-rich remnant created by a combination of ponding and proximal ice-cover deflation during the waning stages of the outflow channel flood event.

Correspondence: Joseph S. Levy, Department of Geological Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA. Tel.: +1 401 863 3485; fax: +1 401 863 2058; e-mail: joseph_levy@brown.edu

Description and setting of the smooth unit

Mangala Valles is an *c.* 800 km long, outflow channel located south-west of Tharsis (Fig. 1). It extends northward from a break in one of the Memnonia Fossae graben, across the southern highlands, and terminates in the northern lowlands at the dichotomy boundary. The geologic units mapped on the valley floor include Amch (younger, early Amazonian channel material), AHmch (older, late-Hesperian/early-Amazonian channel material) and Hmp (late Hesperian plains material) (Zimbelman *et al.*, 1994).

The smooth unit, Amch, stretches from the head of Mangala Valles (−18.1 N, 210.6 E) to points at least 400 km north (−11.7 N, 208.8 E), varying in width from 10 km to < 400 m. MOLA altimetry demonstrates that the unit occurs predominantly in the lowest regions of the channel. The margins of the unit are undulatory and rounded in some locations, and scalloped in others, forming arcuate serrations (Figs 3–5). Where the unit meets the adjacent walls of the channel, or where there is a contact between the smooth unit and the scoured unit on which it is superimposed, the level and uniform surface of the smooth unit is bevelled. From these relationships we can determine the minimum thickness of the unit: *c.* 10–15 m. At the proximal end of the channel, the unit is composed of two layered subunits, displaying similar morphology but different spatial extent (Fig. 5).

Description of associated surface features

Impact craters

Both the smooth unit and the surrounding scoured terrain display impact craters. Primary impact craters are distinguished by raised rims and a generally circular shape (Figs 3–7). Craters range in diameter from 20 to 560 m. Impact crater counts between the scoured surface and the smooth surface are generally similar, with the scoured terrain appearing slightly older than the superimposed smooth unit, consistent with the observed stratigraphic relationships.

Pits

The most striking features observed on the smooth unit are abundant, shallow, round pits (Figs 3–7). Angular

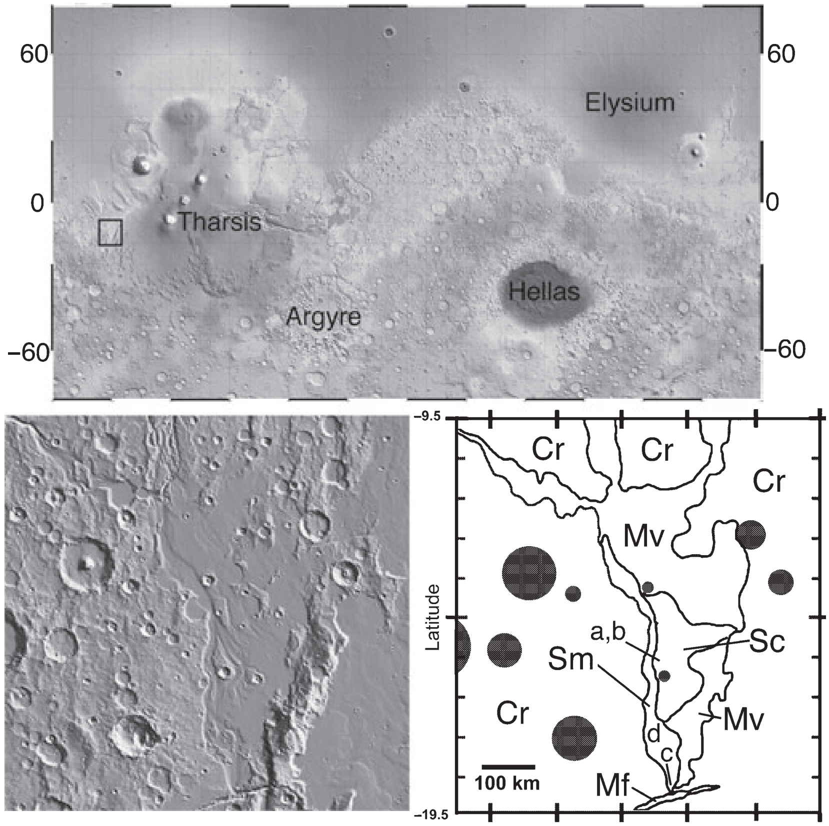


Fig. 1 (Above) MOLA topographic map of Mars showing major surface regions and the Mangala Valles region, boxed, south-west of Tharsis. (Lower left) Shaded relief map of the Mangala Valles region, derived from MOLA data. (Lower right) Sketch map of the Mangala Valles/Memnonia Fossae region showing the location and distribution of the features and deposits associated with the Mangala Valles outflow channel. Mv is Mangala Valles regions not associated with notable features. Mf is one of the Memnonia Fossae graben. Cr marks cratered upland terrain. Sm denotes the smooth unit, and Sc the scoured unit. Significant craters are marked with filled circles. a, b, c, and d mark the locations of THEMIS images V01454001, V06647001, V04762003, and V04400003, respectively. After Zimbelman *et al.* (1994).

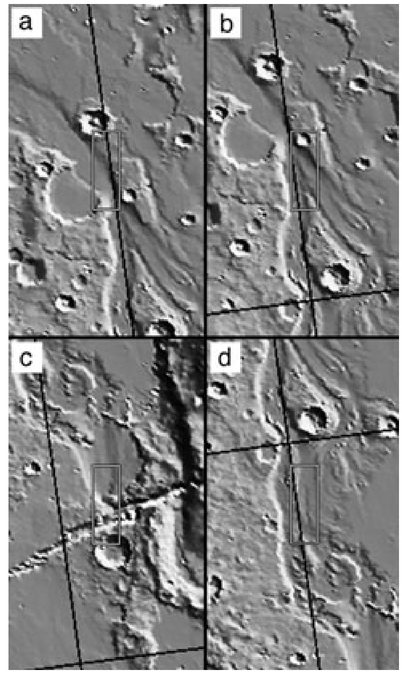


Fig. 2 THEMIS context images for THEMIS images (a) V01454001, (b) V06647001, (c) V04762003, and (d) V04400003. Landmarks in each of the context images can be used to locate high-resolution image locations using the maps provided in Fig. 1. Black lines are synthetic features associated with longitude and latitude lines.

boulders are found at the centres of many pits near the proximal end of the channel (Fig. 7). Most of the pits with blocks have a wide raised rim; however, none of the empty pits have raised rims. Pits with blocks tend to be larger than empty pits; however, the largest pits are empty (Figs 4 and 5). Clusters of pits show signs of coalescence, forming elongated rectangular depressions with long axes sub-parallel to the channel (Fig. 4). There is no apparent spatial preference for pitting density.

Scalloped margins and serrations

The margins of the smooth unit are often serrated with scalloped or cuspate features (Fig. 3). These margin features are often of a comparable size to the pits observed in the centre of the smooth unit. Other portions of the margin are more broadly scalloped (Fig. 3).

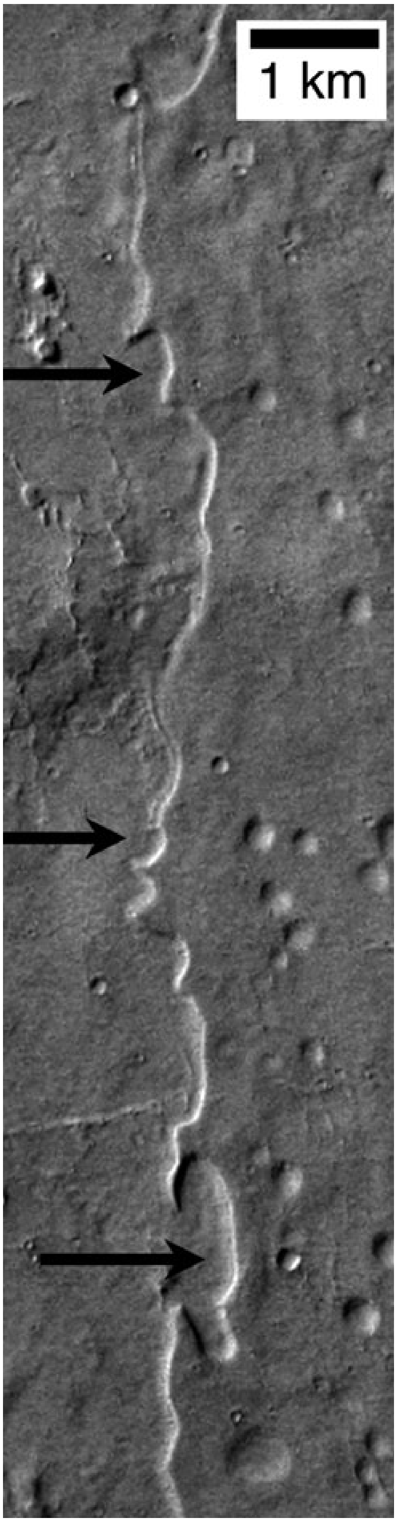
Distal sinuous ridge

In several locations, the width of the unit decreases towards the distal end of the channel, developing into a sinuous feature several hundred metres wide (Fig. 6). The sinuous portion of the smooth unit remains in the lowest reaches of the channels.

Summary of characteristics

The deposits are flat and smooth, at least 10–15 m thick, occur in the lowest portions of the Mangala Valles outflow channel, and are similar in age to the adjacent and underlying intensely scoured valley floor. They show evidence for pitting, marginal scalloping, and a distal braided ridge.

Fig. 3 A portion of THEMIS image V4400003. A scalloped margin delineates the contact between the smooth unit (right) and the scoured unit (left). The rounded and cuspate morphology of the margin suggests that embayments into the smooth unit may be the result of sublimation pits forming near the edge of the unit. Longer embayments may be the result of several pits coalescing near the edge of the smooth unit. Arrows indicate features interpreted to be scalloping associated with pit formation (bottom and top) and more rounded scalloping (centre). Similar margins have been observed in the Tiu/Ares Valles regions of Chryse Planitia and have been interpreted as thermokarst features (Tanaka, 1997, 1999).



Discussion and interpretation

The basic characteristics and stratigraphic relationships of the smooth unit strongly suggest that it formed in association with the waning stages of the Mangala Valles outflow channel event. Following extensive flooding and scouring of the valley, flow velocities would have decreased and floodwaters would have receded until the last stages ponded in low-lying portions of the channel system (Ghatan *et al*., 2005). Furthermore, if global climate conditions were similar to present conditions (as suggested by the presence of glacier-like deposits in the Mangala Valles source region, Head

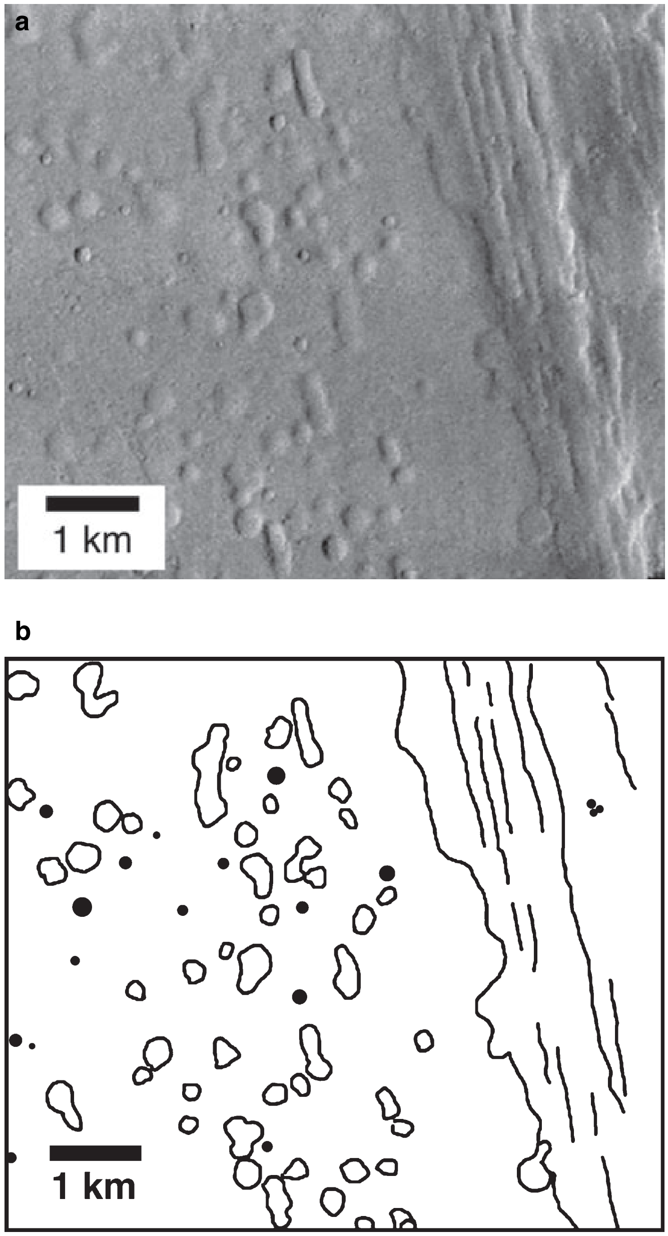


Fig. 4 (a) A portion of THEMIS image V01454001 showing the intensely pitted surface of the smooth unit and the contact between the smooth unit and the scoured unit (right). Pits show some signs of coalescence. We measured the diameters of all 404 pits and 2137 craters in THEMIS images V01454001, V0440003, and V04762003. The pits range in diameter from 100 to 600 m, with a mean of 230 m and standard deviation of 60 m. The image has been stretched to enhance contrast. (b) Sketch map of a portion of THEMIS image V01454001 showing details of pit morphology in the smooth unit. Significant impact craters are marked with filled circles. At right, there is a contact between the smooth unit and the scoured unit.

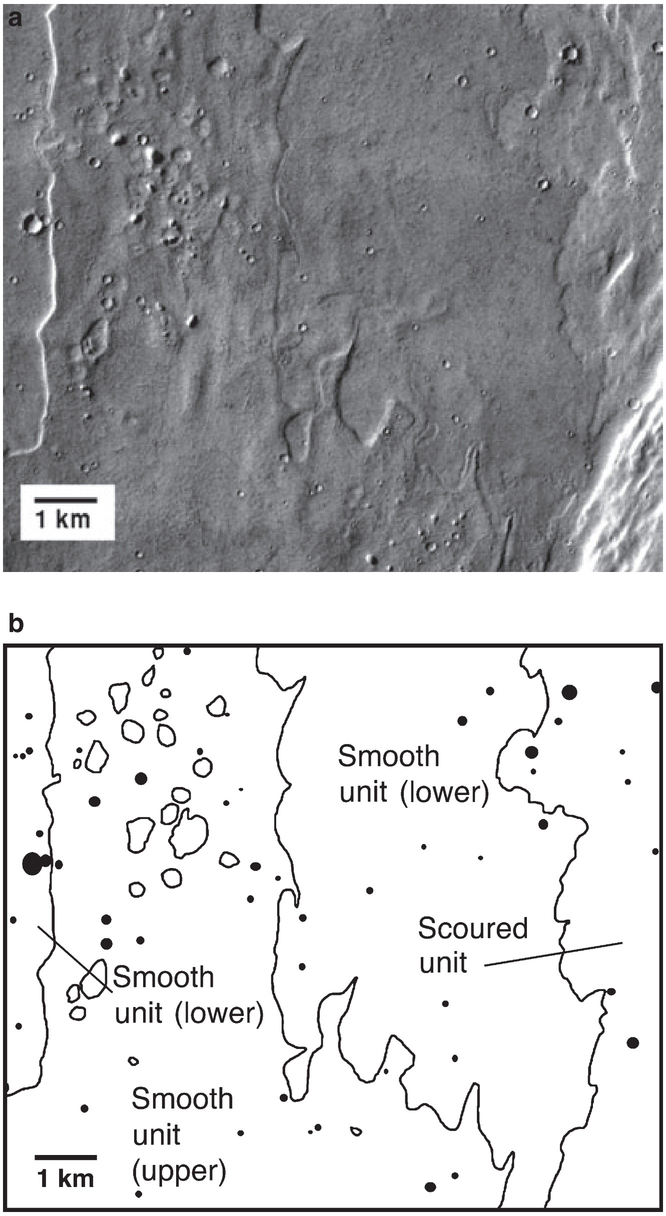


Fig. 5 (a) A portion of THEMIS image V04762003 showing the pitted smooth unit (upper) superposed over a smooth unit with no manifest pitting (lower). The lower smooth unit is superposed on the scoured unit at right. Several boulders are visible on the upper smooth unit, of which some are located within pit boundaries. The image has been stretched to enhance contrast. (b) Sketch map of a portion of THEMIS image V4762003 Pits are delimited by empty loops, and significant craters are denoted by solid circles.

et al., 2004), one would anticipate that the ebbing floodwater surface would have been ice-rich, and that any remaining floodwaters would have rapidly frozen and undergone sublimation (e.g. Kreslavsky and Head, 2002).

The presence of the unit in the lowest reaches of the channel supports a ponding hypothesis (e.g. Lucchitta and Ferguson, 1983), while the partial local draping of the unit over adjacent and underlying scoured terrain suggests deflation of an ice cover, as would have formed atop an outflow flood under cold, dry conditions (e.g. Wallace and Sagan, 1977).

The smooth unit upper layer, interpreted as residue from an ice-rich cap, appears to be preferentially preserved towards the proximal end of the channel. This may be due to a higher concentration of suspended sediment rapidly frozen into the upper ice thermal boundary layer (e.g. Kreslavsky and Head, 2002), or enhanced debris-fall covering the cap unit from the over-steepened walls of the channel's constricted proximal end. Further downstream, turbulent breakup of the ice could have renewed the ice cover with water less rich in suspended sediment, and debris from the adjacent walls could have been less significant. These factors could have resulted in a more ice-rich cap unit at downstream locations that would have been more readily degraded and lost due to the lack of a protective debris-rich cover.

Some investigators (e.g. Lucchitta, 1982) have cited evidence in several outflow channels suggesting that glacial flow may have been a factor in their emplacement and evolution. The lack of elongated craters or pits, streamlines, or cold-based moraines (e.g. Head and Marchant, 2003) argues against a flowing-ice or glacial origin for the smooth unit.

Regarding the origin of the pits, the size-frequency distribution of the pits rules out the possibility that the pits are caused primarily by degradation of impact craters on an ice-rich surface. The impact craters counted on both the smooth and scoured units follow isochron slopes well. In contrast, the pit counts do not follow the $\log_2$ power law associated with cratered terrains (Hartmann, 1977).

What, then, is a plausible origin for the pits? One possible source for the pits is that they represent kettle holes – collapse features associated with ice blocks carried downstream by the outbreak flood flow (e.g. Maizels, 1977, 1992), stranded and surrounded with sediment, before sublimating away, leaving the pit. The relative uniformity of pit size and depth, as well as the distribution of the pits, argues against a kettle origin for all of the pits, although some may have formed in this manner.

Association with the waning stages of a water/ice-rich outflow event suggests that late-stage behaviour of entrained volatiles may also have been a factor in pit formation. Thus, we explore the possibility that the pits in the smooth unit might be thermo-

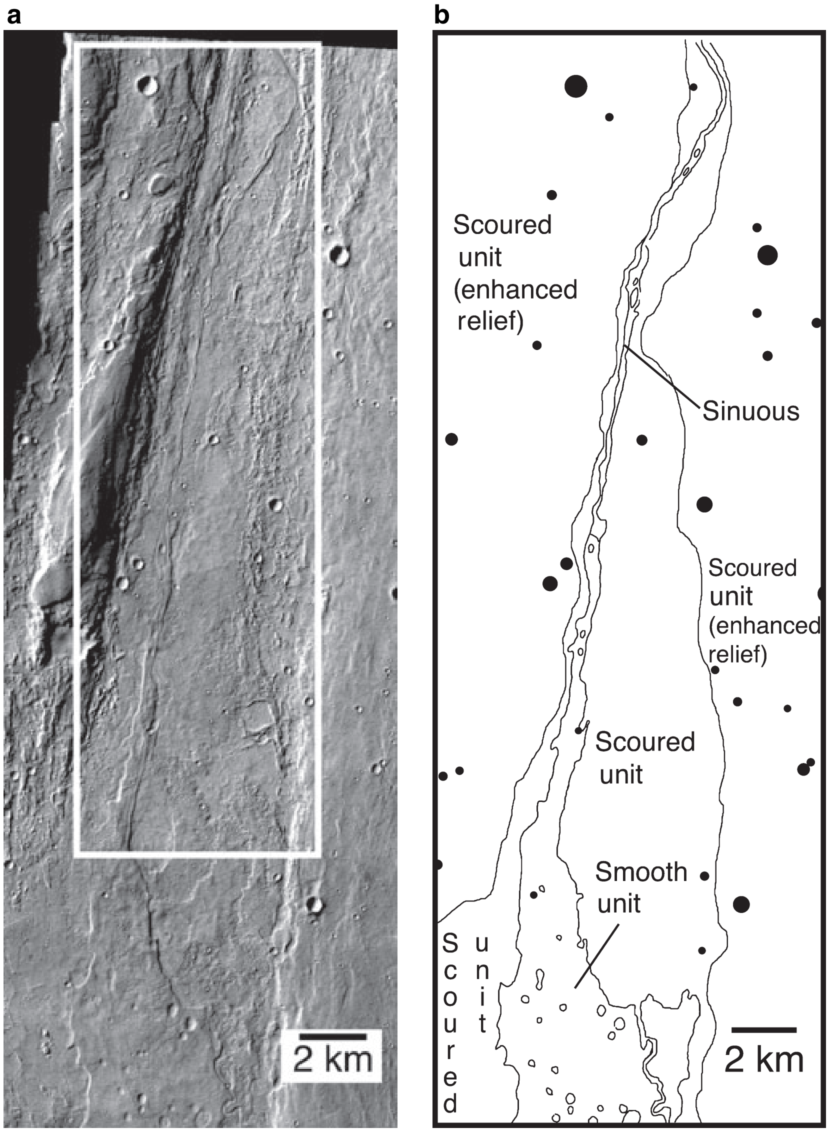


Fig. 6 (a) A portion of THEMIS image V04400003. The smooth unit is observed superposed over the scoured unit. At left and right, enhanced relief of the scoured unit is visible. Above and centre, the smooth unit appears sinuous, and the width of the unit decreases to < 400 m. The sinuous portion of the smooth unit appears to remain in the lowest regions of the channel based on visible geometries. (b) Sketch map of a portion of THEMIS image V4400003. Pits are denoted by empty loops, and significant craters are denoted by filled circles.

karst-like features. On Earth, thermokarst refers to terrain which has features resulting from the thawing of permafrost with excess ice (e.g. Williams and Smith, 1989). We explore this and the likelihood that in the martian environment, sublimation might dominate over melting.

Terrestrial thermokarst pits, known as *alases* (Soloviev, 1973), form through a combination of melt, liquid water flow, and evaporative processes, resulting in the deflation of ice-rich terrain. In Mangala Valles, the discrete shapes of the hundreds of pits, coupled with a lack of interconnecting channels, suggests that the sublimation of near-surface ice, rather than melting, was a dominant factor in the formation of these features. Both terrestrial *alases* and martian sublimation pits form when the thermal equilibrium of an ice-rich unit is disrupted, leading to locally enhanced water mobility due to phase change (melting or sublimation) (e.g. Washburn, 1973).

The interpreted sublimation pits are among the strongest evidence suggesting the presence of extant ground ice in the unit. In terrestrial permafrost terrains where *alases* form, the removal of all ground ice by melting results in the wholesale lowering of the previously ice-rich terrain (e.g. Washburn, 1973). If similar processes are at work in Mangala Valles, the presence of pits, but not entirely lowered terrain, strongly suggests that some ice may still be present in a permafrost-like unit. Had all the ice been removed by sublimation, it is likely that only a mantling layer of sublimation till would be visible.

The scalloped or serrated texture of the smooth unit margin is interpreted to be localities where sublimation and pitting occurred near the margin of the unit (Fig. 3). Longer embayments may be locations where several sublimation pits coalesced, forming an elongated cavity (Fig. 4). Some elongated pits may be the result of enhanced lateral sublimation governed by ice concentrations (e.g. Washburn, 1973), or may be due to preferential sublimation and retreat along the edges of the deposit. The source of this sublimation may be mass wasting along the steeper margins causing local exposure of more ice-rich material. Proximity to the steep sides of the channel walls may also enhance marginal sublimation due to changes in local thermal environments (e.g. Hecht, 2002).

Regarding the origin of the distal sinuous ridge, the morphology of this feature suggests deposition of sediment from fluid flow. Two possibilities are (1) stream deposits that have subsequently been exhumed (inverted topography), and (2) an esker-like feature, deposited subglacially (e.g. Shreve, 1972, 1985). Esker-like deposits imply significantly greater ice-cover of the surface than is presently observed, as well as sub-ice flow of sediment-laden liquid water. We thus prefer an origin by late-stage liquid flow beneath the thickening ice cover.

In summary, the unusual features on the floor of Mangala Valles are interpreted as the sublimation lag deposit derived from an ice thermal boundary layer on the aqueous flood

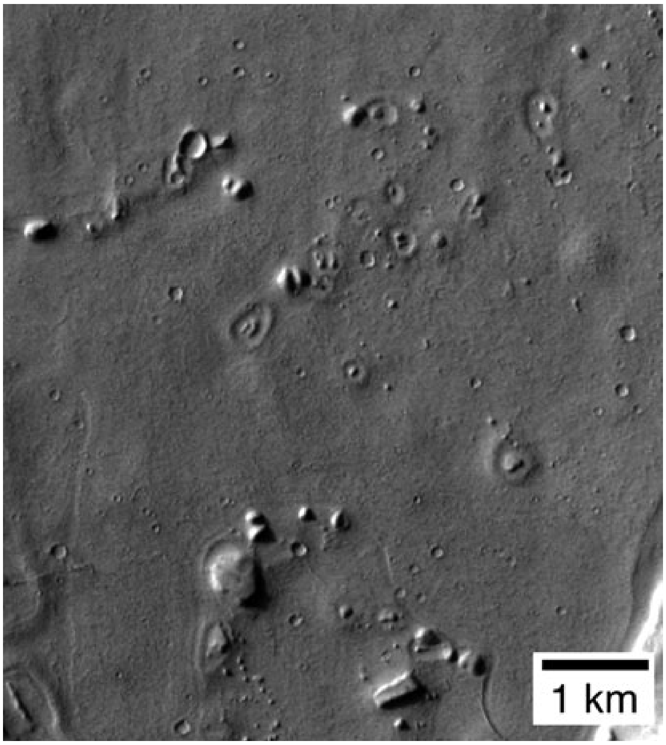


Fig. 7 A portion of THEMIS image V4762003. Only the smooth unit is visible. Numerous pits are visible, some of which contain large boulders. Pits containing boulders frequently have a raised ridge along the perimeter of the pit.

that formed the outflow channel system, and the remnant of waning floodwaters trapped in channel lows. The ice cover deflated, and together with the remnant water–sediment material, froze solid and sublimated, leaving the present deposit as a sublimation residue. In areas of more pure ice (perhaps blocks of ice) or where the sublimation residue has been disturbed, enhanced sublimation has occurred, producing sublimation pits (Fig. 4).

Regarding the possibility of the continued presence of ice in the smooth unit, the hyper-arid polar desert climate of the Antarctic Dry Valleys provides a similar set of environmental conditions under which preservation of near-surface ice for protracted periods has been observed. There is evidence that in Beacon Valley, one of the Antarctic Dry Valleys, near-surface ice deposits have remained intact for 8 Myr or more (Sugden *et al*., 1995). The longevity of these ice deposits represents a significant retardation of expected sublimation rates, and occurs largely due to the evolution of a metre-scale thickness sublimation till which both modulates seasonal temperature variations in the ice-rich layer and reduces net water vapour flux out of the ice-rich unit, significantly reducing net sublimation (Marchant *et al*., 2002).

Conclusions

The identification of an ice-rich residue associated with an outflow flood event strongly suggests that this outflow event occurred on a cold and dry Mars, consistent with other observations of the Mangala Valles source region (Head *et al*., 2004). The stability of the ice-rich smooth unit on the Valles floor provides a constraint to any climatic variation associated with surface to near-surface liquid water flow. The minimal disruption of the smooth unit (limited to localized sublimation pitting and marginal retreat) strongly suggests that any post-deposition warming involved sufficiently low temperatures that the ice-rich unit was not more pervasively disrupted (Soloviev, 1973). Thus, the interpreted preservation of ice-rich debris beneath a sublimation till suggests that climate conditions have remained cold and dry on Mars since the formation of the Mangala Valles outflow channel, and that icy flood residue may be maintained for unprecedented periods of time. The formation of extensive sublimation pits strongly suggests that parts of the remaining deposit may currently be ice-rich.

Extant near-surface, ice-rich deposits in Mangala Valles therefore represent a prospective target for future exobiological investigations. Recent studies of subsurface ice in the Artic and Antarctic have revealed the presence of significant bacterial populations in glaciers and ice-sheets (Karl *et al*., 1999; Miteva *et al*., 2004). These bacterial populations thrive in the freeze-resistant, high-pressure, brine-rich interstices between water-ice grains (Karl *et al*., 1999; Miteva *et al*., 2004). Given the high debris content inferred for the Mangala Valles smooth unit, as well as the association of the outbreak floodwaters with Memnonia Fossae, it is reasonable to suspect that similar environments may exist in the Mangala Valles flood residuum and perhaps in other outflow channel deposits as well (e.g. Fuller and Head, 2002).

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