Formation of Martian outflow channels by catastrophic dewatering of evaporite deposits

David R. Montgomery
Alan Gillespie
Quaternary Research Center, University of Washington, Seattle, Washington 98195-1310, USA

ABSTRACT

Geological mapping based on topographic analysis of Mars Orbiter Laser Altimeter (MOLA) data, together with photointerpretation of Mars Orbiter Camera (MOC) images and thermodynamic and heat-flow considerations, frame a new hypothesis for the formation of Martian outflow channels through catastrophic dewatering of evaporite deposits. MOLA transects across Valles Marineris show that the valley is located at the crest of a 3-km-high topographic bulge on the flank of the much larger Tharsis Rise. Interpretation of MOC images showing layered deposits within Valles Marineris as unconformably underlying Hesperian-age lava flows means that these thick deposits, thought to contain hydrous sulfates, were heated by an increased geothermal gradient due to development of Tharis. Increased temperatures adequate to dehydrate hydrous evaporites would trigger significant volumetric expansion and catastrophically release tremendous amounts of overpressured water.

Keywords: Mars, outflow channels, floods, evaporites.

INTRODUCTION

Processes responsible for forming Valles Marineris and the associated outflow channels (Fig. 1) have proven controversial ever since these features were first recognized during the Mariner 9 mission (McCauley et al., 1972). Although hypotheses offered to explain channels on Mars invoke an array of processes, most workers now consider the major outflow channels to have been formed by huge discharges of flowing water involving a complicated history of repeated flooding related to development of the Tharsis Rise and volcanic field (Carr, 1996; Baker, 2001). The source of enough water to account for the tremendous discharges required to carve the outflow channels remains controversial, as does the genetic relation of the outflow channels to the troughs of Valles Marineris, which most workers interpret as structural grabens or collapse features formed by either extensional tectonics or tensional stresses associated with the development of Tharsis (e.g., Lucchitta et al., 1992). On the basis of new geological mapping and topographic analyses that used Mars Orbiter Laser Altimeter (MOLA) data, interpretation of Mars Orbiter Camera (MOC) images, previously reported evidence for evaporite deposits on Mars, and thermodynamic and heat-flow considerations, we propose a novel hypothesis for the formation of Martian outflow channels through catastrophic dewatering of evaporite deposits.

IMAGE INTERPRETATION AND TOPOGRAPHIC ANALYSES

We superimposed previous geological interpretations (Scott and Tanaka, 1986) on a shaded relief map generated from MOLA data and revised contact locations in accord with relations apparent on the higher-resolution topographic base (Fig. 1). Ignoring unconsolidated surficial deposits and generalizing geological units, we mapped (1) Amazonian lava flows with low crater density and flow indicators both streamlined in the flow direction and deflected around older topographic units; (2) outflow channels cut into Hesperian deposits; (3) moderately cratered Hesperian-age lava flows forming plains with ridges generally orthogonal to flow directions; (4) layered deposits exposed in the interior of Valles Marineris, Hebes Chasma, and Juventae Chasma; and (5) Noachian lava flows in heavily cratered highlands.

The stratigraphic position of light-colored layered deposits in Valles Marineris is contentious. Most workers hold that interior layered deposits are younger than layered materials exposed in the walls of Valles Marineris (e.g., Lucchitta et al., 1994; Chapman and Tanaka, 2001), but Malin and Edgett (2000) reported that MOC images showed interior layered deposits in Valles Marineris to extend beneath darker rock of the upper part of valley walls. Examination of additional MOC images of areas where layered deposits are exposed in Valles Marineris and neighboring Hebes Chasma shows similar relations, with distinctive light-toned layered formations extending under the dark rocks that form the upper canyon walls. In particular, our interpretation of MOC images R08-00286 and R08-00287 places light-toned layered deposits below an erosional unconformity, and thus as exhumed from beneath overlying wall rock on the southern wall of Valles Marineris (Fig. 2).

Topographic transects across Valles Marineris derived from MOLA data show that the chasm is located at the apex of a topographic bulge, ~1900 km wide and locally more than 3 km high, that deforms Hesperian-age lava flows on the eastern flank of the much broader Tharsis Rise. Although centered on the area of extensive exposures of layered deposits within Valles Marineris, the bulge extends beyond those outcrops in all directions. The average height of the bulge within the area across which interior layered deposits are exposed in Valles Marineris is 1.5 km. Elevation of this anomalous terrain and formation of Valles Marineris postdated emplacement of the Hesperian lava flows.

Topographic cross sections interpreted with the aid of geologic mapping and MOC imagery portray interior layered deposits in Valles Marineris and neighboring Hebes Chasma as being locally as thick as 4–6 km, with 1–2 km of overlying Hesperian lava flows forming the surrounding plains. However, interior layered deposits are not everywhere exposed in the walls of Valles Marineris, and Noachian lava flows extend below the younger surficial flows in places to the base of cliff exposures (McEwen et al., 1999). We interpret the geologic relations and topography in the area around Valles Marineris to record deposition of the interior layered deposits inset into the surrounding Noachian highland before the emplacement of Hesperian-age lava flows and the subsequent doming and outburst floods (Fig. 3).

CONCEPTUAL MODEL

Spencer and Fanale (1990) speculated that Valles Marineris and Hebes Chasma formed by collapse after dissolution of carbonate deposits that had been buried beneath Hesperian lava flows, but thus far spectral evidence fails to confirm the presence of carbonates on Mars. Telescopic global spectra have, however, revealed the presence of magnesium sulfates on Mars (Blaney and McCord, 1995), and hydrous magnesium sulfates may be geologically stable near the Martian equator (Feldman et al., 2004). Some workers have interpreted layered deposits in Valles Marineris as evaporite deposits (Beyer et al., 2000; Komatsu and Di Cencio, 2002), an interpretation bolstered by recent spectroscopic identification of hydrous sulfates associated with interior layered deposits exposed along the southeastern wall of Melas Chasma in Val-

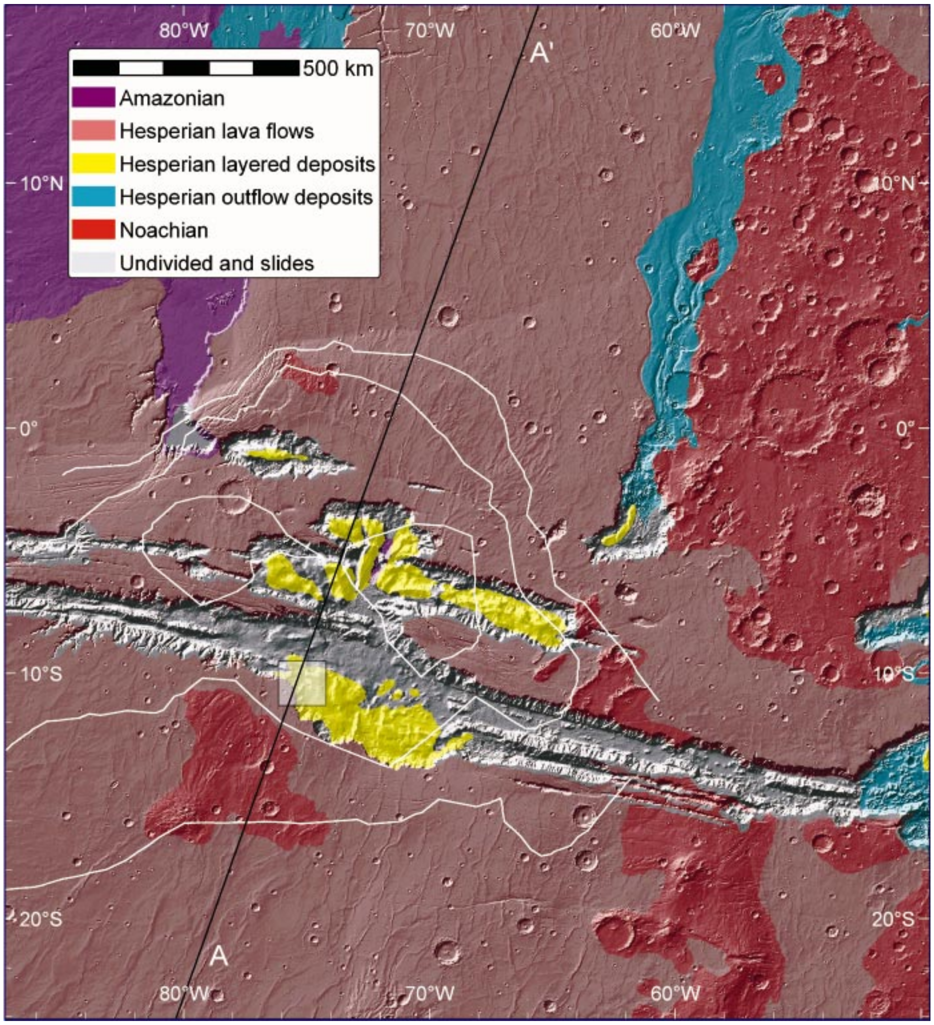

Figure 1. Geological map of region around Valles Marineris. A–A′ shows location of cross section shown in Figure 3. White 1 km contours show detrended elevation of topography above far-field slope of Hesperian lava flows in area of bulge centered on Valles Marineris. Nominal grid size of digital elevation model is ~450 m. Note that outflow channel unit is defined morphologically rather than genetically because it includes both erosional surfaces and deposits. Black square shows location and size of Figure 2.

les Marineris (Mustard et al., 2004) and the discovery of sedimentary rock at Meridiani Planum (Squyres et al., 2004). On the basis of the geologic and topographic relations discussed here, we propose that thermally induced dewatering of thick evaporite deposits produced the tremendous volumes of water that carved Martian outflow channels.

What would have happened if a thick section of Ca, Mg, and/or Na sulfates were overrun by lava flows and/or heated from below during the development of Tharsis? Gypsum ($CaSO_4 \cdot 2H_2O$) dehydrates if heated above 353 K, driving off 75% of the water contained in its chemical structure (Table 1). In the presence of a brine, the reaction proceeds at temperatures as low as 293 K (Berner, 1971). Epsomite ($MgSO_4 \cdot 7H_2O$) is stable at Mars surface conditions of 218 K and 500 Pa (Hogenboom et al., 1995), but begins to dehydrate at ~270 K and rapidly dehydrates at 300 K. Similarly, mirabolite ($Na_2SO_4 \cdot 10H_2O$) dehydrates at ~245 K. Although these reactions are capable of producing large volumes of water, on Mars they require substantial heat input.

Could the development of the Tharsis Rise and eruption of the Hesperian-age lava flows have provided sufficient heat to dewater enough evaporite fast enough to account for the outburst floods that appear to have originated from Valles Marineris and neighboring depressions? Emplacement of lava flows at ~1400 K would transiently heat the upper portions of a buried evaporite deposit, although such an effect would be limited because thin surface flows lose more heat to radiative cooling than to heating of the subadjacent rocks. However, the complementary effect of burial and increased heat flow can be assessed by using the one-dimensional solution to the thermal diffusion equation, for which the depth (Z_d) to a temperature hot enough to dehydrate a mineral is given by

$$Z_d = K_d \, (T_d - T_s)/Q_s, \qquad (1)$$

where K_d is thermal conductivity (W m^{-1} K^{-1}), T_d is the temperature of dehydration, T_s is the average ground surface temperature, and Q_s is heat flow (m W m^{-2}). For the present estimated average heat flow of 30 m W m^{-2} for Mars, average crustal conductivity of 2 W m^{-1} K^{-1}, and average surface temperature of 218 K (Clifford, 1993), the depth of gypsum dehydration would be below 8–13 km, depending on the activity of water (Fig. 4). Hence, a 4–6-km-thick hydrous evaporite deposit would be stable under average conditions on Mars. However, tripling of the heat flow to 90 m W m^{-2} would reduce Z_d to 1.5–3 km. Moreover, the estimated heat flux of 100 m W m^{-2} in the late Hesperian (Stevenson et al., 1983) implies that thick piles of evaporates would have been close to dehydrating even before the development of Tharsis or eruption of lava flows that buried interior layered deposits. Hence, insulation from emplacement of Hesperian-age lava flows and increased heat flow associated with development of Tharsis, such as could occur from subsurface emplacement of a hot dike (McKenzie and Nimmo, 1999), would have heated even thick deposits of evaporates past the point of dehydration.

The volume change and amount of water generated upon dehydration varies for differ-

TABLE 1. TEMPERATURE AND CONSEQUENCES OF DEHYDRATION REACTIONS FOR HYDROUS SULFATE EVAPORITES

Dehydration reaction	Volume dehydrated salt / Volume hydrated salt	Volume water / Volume hydrated salt	Volume "excess" water / Volume hydrated salt
Gypsum-bassanite (353 K) $CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 \cdot 0.5H_2O + 1.5H_2O$	0.84	0.31	0.16
Epsomite-kieserite (300 K) $MgSO_4 \cdot 7H_2O \rightarrow MgSO_4 \cdot H_2O + 6H_2O$	0.56	0.88	0.44
Mirabilite-thenardite (245 K) $Na_2SO_4 \cdot 10H_2O \rightarrow Na_2SO_4 + 10H_2O$	0.44	1.12	0.56

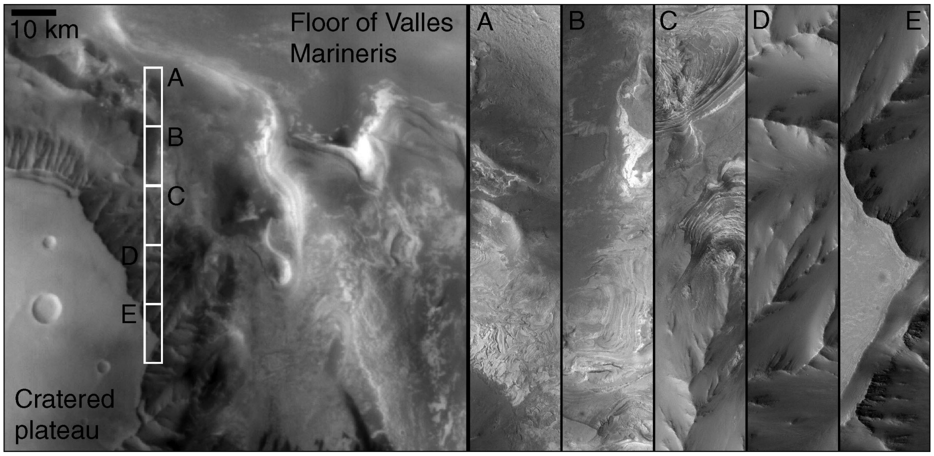

Figure 2. Mars Orbital Camera (MOC) images R08-00286 (detailed image) and R08-00287 (context image) showing crosscutting relation of contact between interior layered deposits and overlying valley wall–forming lava flows. We suggest examining higher-resolution image from top of page (i.e., upside down) in order to see image more clearly. Halfway down image, contact between overlying dark material and underlying light-toned layered deposit truncates beds of interior layered deposit, consistent with interpretation of contact as erosional unconformity; similar relations are seen in MOC images of Candor Chasma (M17-00467, M14-00631, M19-00784, R07-00897), Coprates Chasma (M20-01760), and Melas Chasma (R04-01897, R08-00286, R08-01525) in Valles Marineris, as well as in Hebes Chasma (M09-00284, R04-00640) and Juventae Chasma (M10-00466).

ent hydrous evaporites, but all three of the reactions discussed here lead to overpressurization and expansion (Table 1). Heating sufficient to melt permafrost and dehydrate evaporites results in an initial volume decrease due to melting of ice, followed by expansion, cracking, and, once drained, release of overpressured water. Assuming that the interior layered deposits are entirely composed of evaporite, with no permafrost, and that both the hydrous evaporites and their dehydration products have a density of 2 g cm^{-3}, then for each cubic centimeter of initial deposit, the dehydration reactions produce 0.31–1.12 cm^3 of water and only 0.16–0.56 cm^3 of void (pore) space. Consequently, complete dehydration of a 4–6-km-thick column of these evaporite minerals would produce 0.6–3.4 km of hydraulic head, most likely accommodated by volumetric expansion in the least-confined dimension (vertical). If such a pile extended only across the ~1000-km-diameter area across which interior layered deposits are exposed in Valles Marineris (a range in total deposit volumes of 3.1×10^6 to 4.1×10^6 km^3), these reactions could potentially produce 1×10^6 to 5×10^6 km^3 of water. There is much uncertainty about mineral densities appropriate for composite evaporite deposits, the extent and potential effects of lithic dust incorporated in the interior layered deposits, and the effects of melting ground ice on the amount of overpressured water. For these reasons, among others, we consider these calculations to be first-order illustrative calculations rather than specific predictions. Still, these order-of-magnitude estimates indicate the potential for this novel mechanism to produce copious amounts of overpressured water.

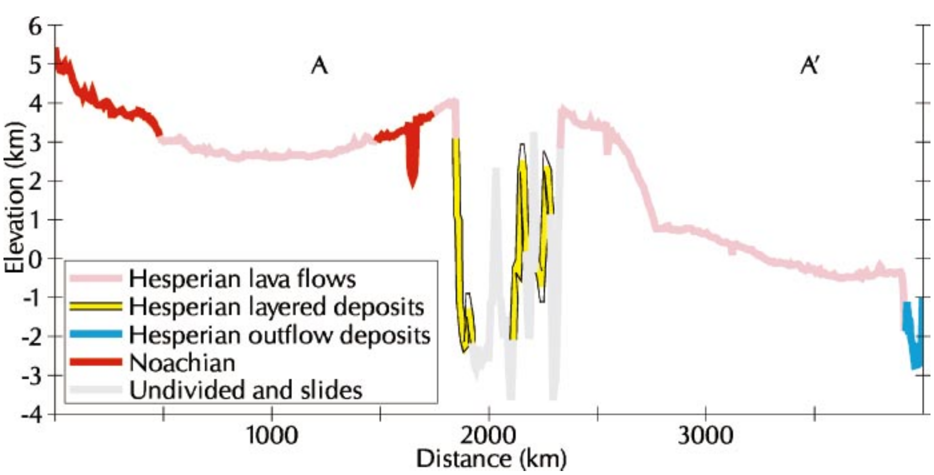

Figure 3. Topographic profile across Valles Marineris showing geological units exposed at ground surface and illustrating distinct topographic bulge associated with Valles Marineris. Note vertical exaggeration of 180:1.

Models of fluid-pressure feedback during dehydration reactions indicate the potential for positive feedback to result in rapid, catastrophic dewatering of even large deposits (Miller et al., 2003). Overpressured fluids can induce local hydrofracturing that creates a small-scale crack network in a self-organizing process through which large fluxes can occur over short time spans (Bons and van Milligen, 2001). Reduced local fluid pressure from the introduction of a drained boundary accelerates the dehydration reaction at all locations connected to the boundary, leading to focused fluid expulsion and driving the system further into the field of the anhydrous phase (Miller et al., 2003). In such a scenario at Valles Marineris, once the overlying seal of the cap rock was broken, the exposure of overpressured fluid conduits to the Martian atmosphere would have triggered catastrophic drainage along a few primary conduits.

DISCUSSION

Could early Martian history account for the presence of substantial deposits of sulfate-rich evaporites? On the basis of morphologic analogs in terrestrial environments, Forsythe and Zimbelman (1995) argued for extensive deposition of evaporites during the Noachian epoch. The immense thicknesses of evaporites invoked here requires a basin for accumulation, such as a large crater or the structural basin proposed by Dohm et al. (2001b) as underlying eastern Tharsis. Bombardment of the Noachian highland would have introduced copious amounts of pulverized rock into the atmosphere, possibly catalyzing episodic dust-rich precipitation. Accumulation of thick evaporites could have resulted from multiple cycles of evaporation of sulfate-rich runoff or groundwater flow into terminal drainages. Layering in the resulting deposits may record variations in climatic or orbital forcing, zonation among different evaporite minerals, or variations in the percentage of clastic material.

Dohm et al. (2001a) argued that the growth of Tharsis generated immense outburst floods to the west well before the genesis of Valles Marineris. These earlier paleofloods could have been produced by the same mechanism proposed for Valles Marineris. Relatively brief episodes of elevated heat flow during the development of Tharsis would be consistent with repeated local cataclysmic heating of evaporite sequences to generate a complex history of outburst flooding across the region.

Although the catastrophic dewatering of massive evaporite deposits provides a simple explanation for major Martian outflow channels, two issues are problematic. Generating

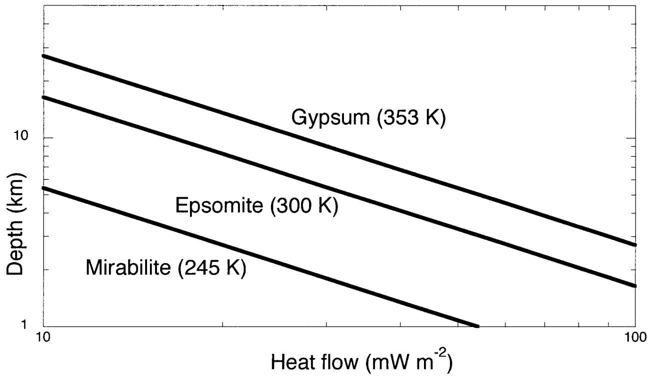

Figure 4. Depth below ground surface required to elevate temperature to melting point of gypsum (353 K), epsomite (300 K), and mirabilite (245 K) (Sonnenfeld, 1984; McCord et al., 2001). Predicted depths are based on one-dimensional steady-state heat-flow model (equation 1), assuming average surface temperature of 218 K and average thermal conductivity of 2 W m^{-1} K^{-1}.

high hydraulic heads in highly porous volcanic flows requires either rapid heating or a confined aquifer, such as could be generated by localized heating within an active cryosphere. In addition, dewatering the sulfates would require geothermal heat necessary to overcome the latent heats of fusion for any permafrost or ground ice and the dewatering reactions. Although we can estimate the steady-state temperatures for a given heat flux, we don't know the duration of increased heat flow, so at this stage we simply assume they were long enough to overcome the heat of fusion. Our hypothesis does not require substantial ground ice, although its presence would increase the amount of water available. Dewatering would have been self-terminating after forming a few large valleys, which may help explain the long linear nature of Valles Marineris. We also acknowledge that the area of the bulge is larger than the mapped exposure of interior layered deposits, and that for dewatering of shallowly buried evaporites to cause the bulge requires the actual area of the interior layered deposits to be larger than the area exposed to view.

We do not mean to imply that all channels on Mars were created by dewatering of evaporites. Nevertheless, we suspect that even in other locations not insulated by the Hesperian lava flows, such as where craters held evaporites or where the regolith was rich in hydrous salts, it is possible that transient heating of evaporite minerals could have triggered dehydration reactions to cause local flooding and the formation of channels smaller than those discussed here.

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