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Volatile History of Mangala Valles, Mars

JAMES R. ZIMBELMAN AND ROBERT A. CRADDOCK

Center For Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C.

RONALD GREELEY

Department of Geology, Arizona State University, Tempe

RUSLAN O. KUZMIN

Vernadsky Institute, Russian Academy of Sciences, Moscow

Mangala Valles are unique among Martian outflow channels because they emanate from a point source determined by the interaction of tectonism, volcanism, and volatile migration. Present topography and morphology place constraints on the magnitude of the discharge into the channels, supporting a release of water which spanned from tens to thousands of days. The sequence of events associated with the release of volatiles in the southern (proximal) reaches of Mangala Valles indicates that structural features around the source area played a crucial role in determining the location of the apparent source of volatile release onto the Martian surface. Postulated locations for storage of the water released into the Mangala Valles system include aquifer systems in the highlands south of the release point, within the layered flows of the Tharsis plains, and a surface lake in the Daedalia Planum area. Hydraulic conductivity within the aquifer could have inhibited a sudden release of all the stored water, lengthening the total discharge duration toward the longer time frame indicated above. Topographic and structural constraints favor groundwater flow from the Tharsis region, which may have manifested itself at the Mangala source area as an artesian flow. Fluid release into the Mangala Valles system likely included sheet flows and episodic surges of water resulting from temporary ice dams within the channel system and may have included releases from more than a single location.

INTRODUCTION

The Memnonia region of Mars contains a remarkably diverse collection of geologic features and terrains, including ancient cratered highlands, sparsely cratered smooth plains, young volcanic plains, and the Mangala Valles channel system (Figure 1). The streamlined landforms and braided channels of Mangala Valles were recognized as strong indicators that this area was subject to substantial erosion by a flowing fluid, most likely water [*Milton*, 1973; *Sharp and Malin*, 1975]. Recently, the best Viking images of the southern (proximal) reaches of Mangala Valles (Figure 2) were examined as part of the 1:500,000-scale geologic mapping of the entire Mangala Valles area [*Chapman et al.*, 1989; *Tanaka and Chapman*, 1990; *Chapman and Tanaka*, 1992; *Craddock and Greeley*, 1992; J.R. Zimbelman et al., map in review, 1992]. Improved processing of some of the images reveals important details that were not available in previous studies. This paper describes several components of the complex history of Mangala Valles that have been identified as a consequence of detailed mapping of the southern reaches of the channel system and shows the relationships to the materials preserved in the northern reaches [*Tanaka and Chapman*, 1990].

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REGIONAL SETTING

Mangala Valles are located in the Memnonia region of Terra Sirenum, southwest of the Tharsis Montes volcanoes and south-southeast of Amazonis Planitia (Figure 1, black pattern). Northeast-southwest trending grabens, collectively named Memnonia Fossae, cut across the region south of Mangala Valles. Memnonia primarily consists of densely cratered plains typical of much of the southern hemisphere of Mars, with the relatively young plains associated with Tharsis volcanism to the east and lightly cratered but extensively modified plains to the north [*Scott and Carr*, 1978; *Scott and Tanaka*, 1986]. In general, the southern cratered highlands are separated from the northern lowland plains by a scarp averaging about 2 km in height, but in the Memnonia region the topographic expression of the boundary is considerably lower and is buried by Tharsis lavas east of 140°W longitude [*Scott and Tanaka*, 1986].

The study area encompasses the western boundary between the Tharsis plains and the cratered highlands, which run north-south at this location. The central channel of Mangala Valles heads at a breach in the northern wall of one of the largest Memnonia Fossae grabens (18°S, 149°W), interpreted to be the source of the Mangala Valles floods [*Carr*, 1981, p. 147]. *Sharp and Malin* [1975] interpret Mangala Valles as "outflow" channels where overflow may have breached a reservoir holding a large lake, which led to rapid outflow. On Earth, the Lake Missoula Flood of the Pacific Northwest produced a distinctive drainage pattern and erosional features

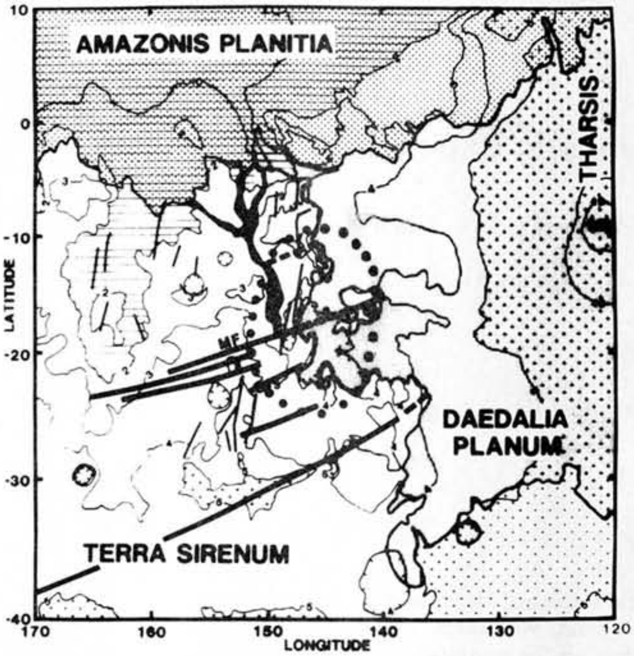

Fig. 1. Regional setting of Mangala Valles in the Memnonia region of Mars. Topography [from *U.S. Geological Survey* (USGS), 1989] shown in narrow contours; areas below 2 km have lined pattern; areas above 5 km have cross pattern; contour interval equals 1 km between 2 and 5 km elevation. Contours enclosing an area lower than surroundings have interior tick marks. Geologic provinces [after *Scott and Tanaka*, 1986] are separated by thick lines; Mangala Valles channels have black pattern, northern lowlands have large dot pattern, Tharsis plains have small dot pattern (AM, Arsia Mons), and cratered highlands have white pattern. Major grabens are shown by thick lines (MF, Memnonia Fossae); major scarps are shown by thin lines. Large dots outline possible artesian basin around source of Mangala Valles channels.

in the "channeled scablands" that are similar to features in Mangala Valles [*Baker and Milton*, 1974]. *Tanaka and Chapman* [1990] present a scenario in which the flood waters for Mangala Valles were derived from an aquifer within the cratered highlands, breached by faulting associated with the Memnonia Fossae graben.

The heavily cratered highland materials in the Memnonia region include numerous north-south trending linear to arcuate scarps [*Zimbelman*, 1989*b*]. Earth-based radar topography data show topographic relief in excess of 2 km in the southern Mangala Valles area [*Downs et al.*, 1973, 1975] that correlate with scarps in the ancient Noachian materials (Figure 3). Stereo images of the proximal portions of Mangala Valles show the prominent north-south scarps as well as subtle relief indicating vertical adjustments between separate blocks of terrain (Figure 4). The major north-south scarps all are confined to units mapped as Noachian in age [*Scott and Tanaka*, 1986]. An age older than early Hesperian is consistent with earlier work that showed that these large structures are not related to stresses predicted for theTharsis region [*Schultz*, 1985].

Stratigraphy

Formal stratigraphic systems for Mars include, from oldest to youngest, the Noachian, Hesperian, and Amazonian systems [*Scott and Carr*, 1978; *Tanaka*, 1986]. Although absolute ages for Martian geologic units remain controversial

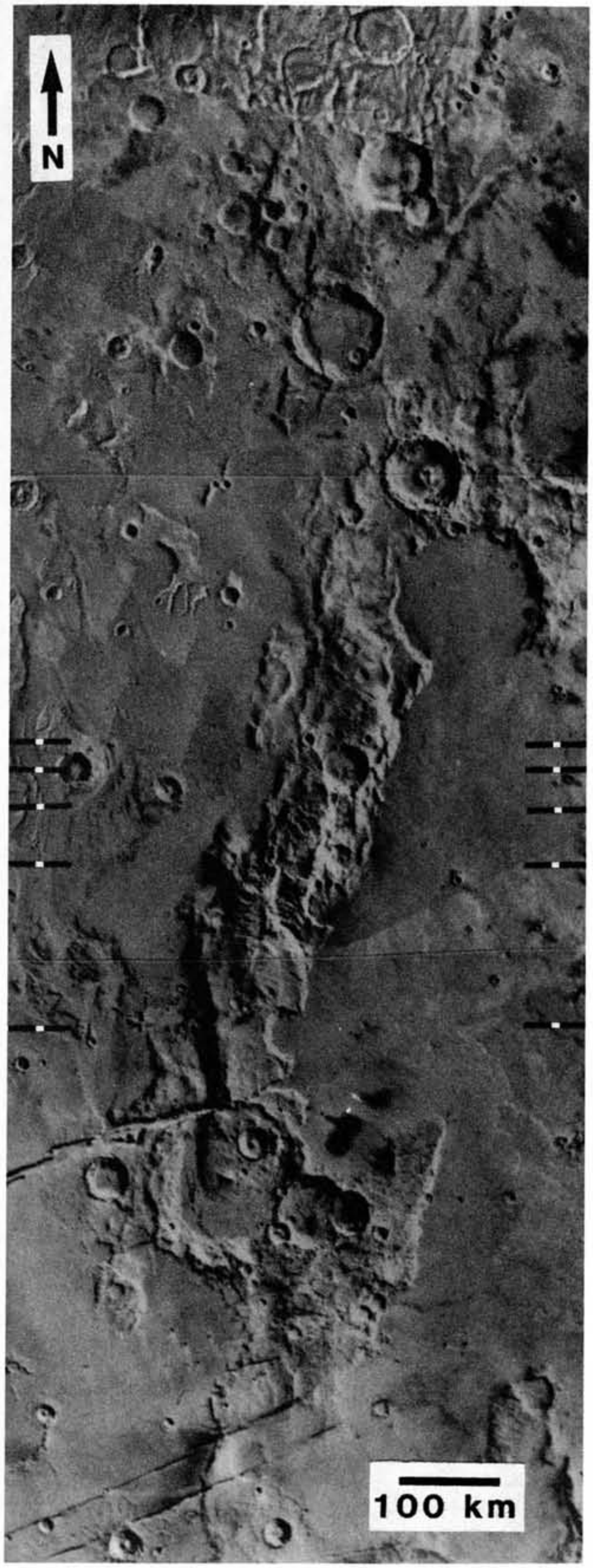

Fig. 2. Southern Mangala Valles region, proximal to the channel source at a breached graben in the Memnonia Fossae system of grabens radial to Tharsis. The area shown (latitude 23°S to 7°S, longitude 144°W to 151°W [*USGS*, 1985*a*,*b*,*c*]) includes the three 1:500,000-scale geologic maps produced by the authors as part of the Mars Geologic Mapping Program. Dashes indicate locations of topographic profiles shown in Figure 3.

[*Neukum and Wise*, 1976; *Hartmann et al.*, 1981; *Neukum and Hiller*, 1981], *Tanaka* [1986] has subdivided the Martian systems into series based on impact crater frequencies, and this scheme is followed here. Relative ages of units described are presented as the number of craters greater than either 2 or 5 km in diameter, N(2) or N(5), expressed as the cumulative number of craters greater than or equal to the specified diameter [N(x)] per 10^6 km^2. Numerous units were identified in the mapping but only those units relevant to the release of volatiles into Mangala Valles (labeled in Figure 4*c*) are discussed below.

Noachian System. The oldest materials in the map area (Figure 2) are plataeu materials (Npl) which form heavily cratered highlands west of Mangala Valles (N(2) = 2000 ± 450, N(5) = 1400 ± 400). The subdued appearance of craters adjacent to the Mangala Valles source graben suggests that shallow sheet flow or low-viscosity lava effusion may have preceded localization of the fluid release at the graben breach.

The hilly and mountainous unit (Nplh) (N(2) = 1350 ± 300, N(5) = 620 ± 210) comprises a ridge 2 km high that separates Daedalia Planum and the Tharsis plains to the east from the Mangala Valles deposits to the west. The Nplh materials are interpreted to be volcanic and impact-brecciated rock uplifted during tectonism and/or impact basin formation [*Scott and Tanaka*, 1986]. *Craddock et al.* [1990*a*] identified this ridge as part of an inner ring related to a 4500-km-diameter impact basin centered at 26°S, 125°W, in Daedalia Planum. The scarp forming the western margin of the Nplh

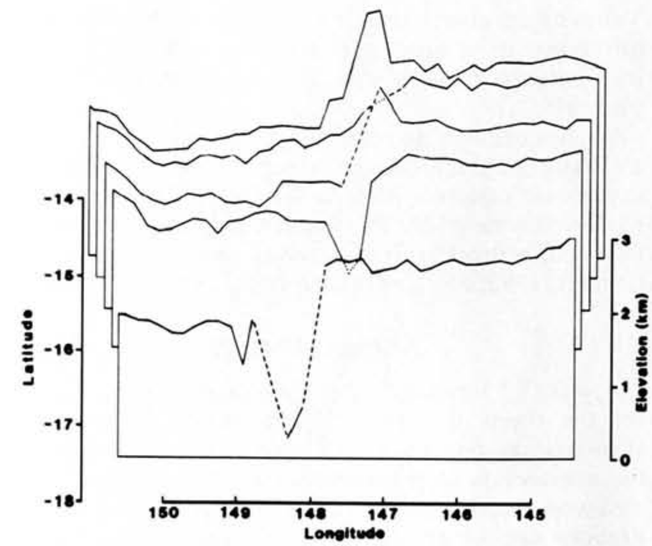

Fig. 3. Five topographic profiles of Mangala Valles obtained from Earth-based radar measurements [*Downs et al.*, 1973, 1975]. The profiles are shown with a vertical exaggeration of 57X; elevation scale is shown at right. The bottom of each profile corresponds to the data groundtrack; latitude is indicated at left. The greatest relief is associated with north-south trends scarps in the ancient Noachian materials. Profiles are dashed across locations where radar measurements were not available, most likely due to scattering by the large local relief, and are dotted where covered by another profile in this view.

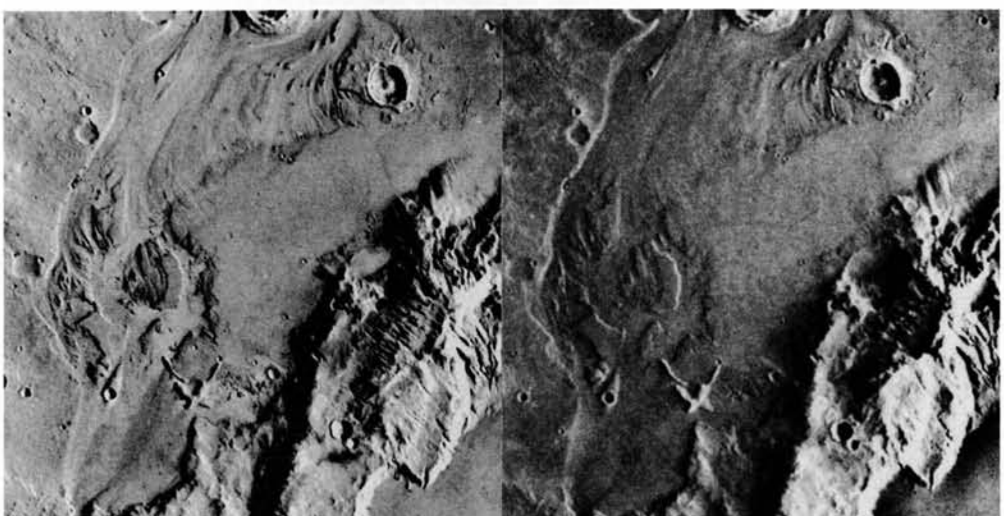

Fig. 4. Stereo pair of proximal portion of Mangala Valles. (*a*) Viking frame 637A82, centered at 17°S, 149°W. (*b*) Viking frame 639A11. (*c*) Sketch of main structural and geologic features. See text for unit descriptions. Arrows indicate scour marks oriented perpendicular to the Hp unit boundary rather than parallel to the main channel orientation. Line A incidates portion of breach channel used for calculations listed in Table 1. Shaded pattern (on unit Nplh) indicates the rotated crustal block with northward dip. Structural symbols show grabens (line with superposed ball), scarps (line with bar and ball on lower side), and a thrust fault (line with barbs on upper plate) evidenced by a 20-km-diameter crater truncated by the fault.

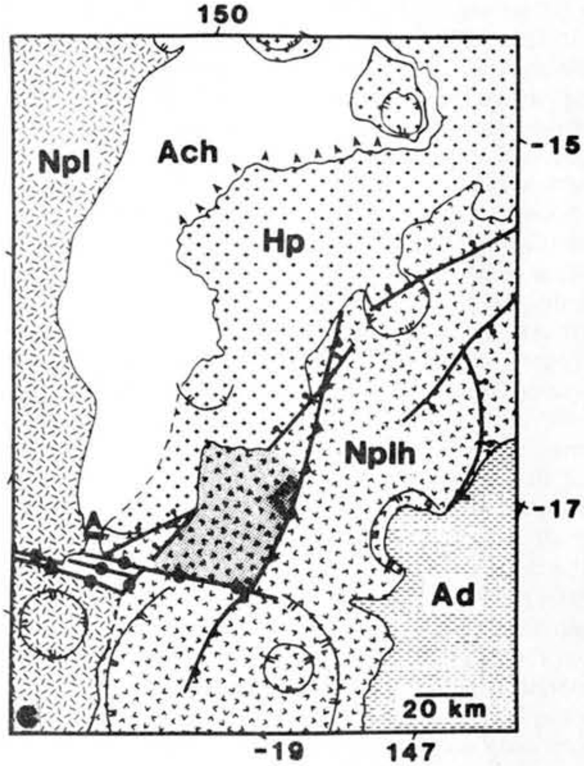

Fig. 4. (continued)

materials truncates the eastern one-third of a 20-km-diameter crater (Figure 2). This scarp is interpreted to be a major compressional fault, the relief of which constrained the overland flow within Mangala Valles to follow a northerly route. A portion of the highland materials adjacent to the scarp appears to have rotated slightly to the north [*Craddock et al.*, 1990*b*]. The scarp and the rotated fault block both may have constrained the flow of volatiles through the regolith and their subsequent release to the surface, as well as provide a conduit for intruded magmas to reach the surface.

Hesperian System. The lobate plains (Hp) (N(2) = 460 ± 130, N(5) = 150 ± 60) have arcuate margins that has been scoured and truncated by later channel materials. Unit Hp is the only areally extensive Hesperian unit within the southern reaches of Mangala Valles. Streamlined features within tens of kilometers of the western margin are oriented obliquely to the direction of the main Mangala Valles flood events, possibly resulting from internal flow along porous or permeable interbeds.

Amazonian System. East of the ridge of Noachian materials are the lobate plains materials of Daedalia Planum (Ad) (N(2) = 320 ± 110). This unit is interpreted to be volcanic lava flows associated with member 3 of the Tharsis Montes Fm [*Scott and Tanaka*, 1986]. However, these materials have lobate flow fronts which face eastward, indicating a source toward the highlands ridge rather than the Tharsis Montes. *Craddock et al.* [1990*b*] suggested that some of these lavas may have erupted from deep-seated faults related to the Daedalia basin, analogous to mare deposits seen in lunar basins. Unit Ad radiates from a small canyon that is an extension f the Mangala Valles source graben, so that they may be either lava or mud flows associated with the flood events from the source graben. *Tanaka and Chapman* [1990] interpret these materials as identical to the Mangala Valles lobate plains (Hp) described above. We note a slight difference in relative age between these units, but the interpretation of both units as volcanic in origin remains plausible.

An Amazonian age for the Mangala Valles channel materials (Ach) is indicated by superposition and the lack of superposed craters > 2 km in diameter. This unit occupies the lowest areas within the channels and may contain exposed (scoured) bedrock, fluvial deposits, or both [*Craddock and Greeley*, 1992; J.R. Zimbelman et al., map in review, 1992].

VOLATILE HISTORY

Mapping of Mangala Valles shows numerous local sources for the fluids that eroded parts of the valley system. However, the primary source appears to be associated with the intersection of the dominant north-south fault and the east-west trending grabens of the Memnonia Fossae. These grabens can be traced northeast into the Tharsis Rise (Figure 1), a topographically elevated region of volcanic origin. Several investigators have related the structures to crustal deformation associated with the growth of the Tharsis province [e.g., *Wise et al.*, 1979; *Plescia and Saunders*, 1982].

Unit Hp may be volcanic materials erupted from now-buried vents prior to the initial flooding of Mangala Valles. Eruptions may have evacuated a magma chamber near the source graben of Mangala Valles, possibly associated with rotation of a polygonal fault block northeast of the breached graben [*Craddock et al.*, 1990*b*]. Subsequent flood waters migrated under the Hp flows, to be released farther down slope along the western margin of the unit; this resulted in streamlined islands oriented perpendicular to the Hp margin rather than aligned with the main Mangala channel (Figure 4*c*, arrows). Alternatively, the lobate front may have been eroded and streamlined by plucking action during flood stage, in which case the eroded front could represent coalesced cataract scarps in the more competent Hp materials (M. Chapman, personal communication). However, the orientation of nearby streamlined features would then indicate that the water came over the surface of the Hp materials, following a path more than 200 meters higher than the topographic low associated with the main channel (Figure 3). It appears that the combined volcanic/tectonic activity of the region led to unique conditions necessary not only to allow migration and concentration of a substantial volatile reservoir but also to allow the volatiles to be released to the Martian surface.

The release of fluids to form the Mangala Valles may also be related to endogenic processes in the Tharsis region. Growth of the Tharsis Rise in the early Hesperian is documented by older fractures of the Memnonia Fossae that cut Noachian age materials and are then partly buried by younger rocks [*Plescia and Saunders*, 1982; *Scott and Tanaka*, 1986]. Subsequent magmatic activity in the southern Tharsis region, such as parasitic volcanic deposits on the southern flanks of Arsia Mons [*Roth et al.*, 1980], may have been responsible for the generation of melt water by heating ground ice trapped within early stage lava flows and the underlying regolith. The permeability of fractured lava flows can be high, attaining values from 10^{-2} to 10^{3} darcies [*Freeze and Cherry*, 1979, p. 29], as illustrated in drainage associated with the basaltic lavas of the Snake River plains in Idaho [*King*, 1977]. Salts, commonly associated with volcanic deposits, could have been mixed with the meltwater, lowering its freezing point and enabling it to remain fluid for a longer time than for pure water [*Zent and Fanale*, 1986].

We suggest that the meltwaters flowed downslope from the Tharsis Rise, beneath ground ice which acted as an aquaclude, following the Memnonia Fossae until they intersected the north-south fault near the present Mangala Valles. Where the fault and the Memnonia Fossae intersect, the meltwater found a ready conduit to the surface. Water may have emerged under pressure, resulting from artesian conditions developed during the subsurface flow away from the Tharsis Rise (outlined area in Figure 1), and flowed northward down the local regional slope across the cratered upland terrain. With no well-defined channel in this early stage of flooding, flow would have been chaotic as the fluid found its way down slope to the north. Crusts of ice may have formed on the surface meltwaters, producing local ice dams in the rugged cratered terrain. Detailed mapping shows that much of the uplands in the distal Mangala Valles are locally pitted and scoured [*Chapman and Tanaka*, 1990]. We suggest that this morphology in the southern Mangala Valles region (Figure 5) may have resulted from an early stage sheet flow of mixed meltwater and ice slush. Local breakouts from ice dams as well as isolated local sources may have contributed to the formation of the small, discontinuous channels observed along the northern extent of Mangala Valles [*Tanaka and Chapman*, 1990].

The development of the Tharsis volcanics should have produced a substantial local perturbation in the permafrost distribution within the Martian crust (Figure 6). Observational [*Kuzmin et al.*, 1988] and theoretical [*Fanale et al.*, 1986] evidence support the presence of a desiccated zone within the uppermost 300 m of the equatorial crust on

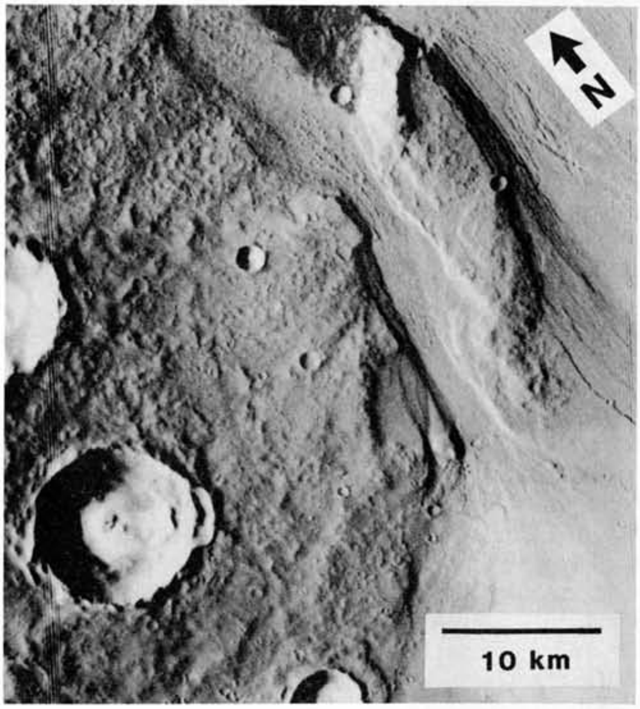

Fig. 5. Scoured surface texture of highlands (left) near the proximal reaches of Mangala Valles (right). The texture is interpreted as surface manifestations of ice and water associated with early stage sheet flow of meltwater and ice slush, perhaps resulting from temporary ice dams in the main channel. Viking frame 450S28, centered at 11.5°S, 152°W.

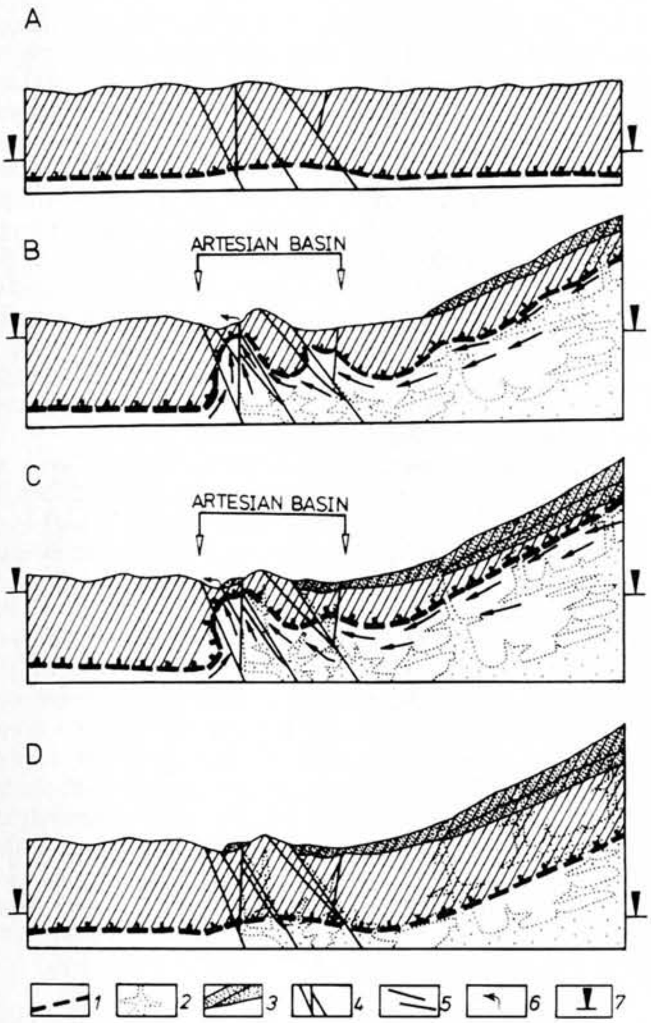

Fig. 6. Cross sections showing the migration and release of underground water between the southern highlands and the elevated Tharsis region. (*a*) Martian crust before the development of the Tharsis region, under a stable thermal regime. The cratered highlands are cut by faults associated with the outer rings of the Daedalia impace basin [*Craddock et al.*, 1990*a*]. (*b*) Uplift of the Tharsis region (right) with associated magmatic intrusions produces an unstable thermal regime within the crust. Increase in heat flow was accompanied by melting of the permafrost layer and upward migration of its lower boundary. Groundwater moved downslope to form an artesian basin near the faulted crustal blocks. (*c*) Volcanic activity extends into the Mangala region under unstable thermal regime within the crust. Instrusive activity along the fault system leads to lava flow emplacement within the Mangala Valles system. Episodic discharge of groundwater from the artesian basin causes local flooding and ponding. (*d*) Martian crust at present, with a stabilized permafrost boundary in a stable thermal regime. Legend: 1, permafrost lower boundary; 2, magmatic intrusions; 3, lava deposits; 4, fault system; 5, groundwater flow; 6, artesian springs; 7, water table.

Mars. *Fanale et al.* [1986] suggest that the permafrost distribution was established early in the geological history of Mars, and we will assume that the thermal regime and thickness of the Martian permafrost zone prior to the growth of the Tharsis volcanoes were similar to the present period (Figures 6*a* and 6*d*), although we recongnize that diffusive loss of equatorial ground ice has slowly lowered the overall depth of the dessiccated zone since sublimation first began. Recent estimates place the thickness of the permafrost in the equatorial regions of Mars between 2 and 3 km [*Kuzmin*, 1983; *Crescenti*, 1984]. However, since magmatic activity can increase the local heat flow by at least a factor of 2 [*Moiseynko and Smyslow*, 1986], the volcanic and magmatic activity associated with Tharsis may have strongly affected the ground ice distribution in the entire region.

If we assume that the heat flow doubled during the period of Tharsis activity, it is possible that the permafrost thickness may have decreased by a factor of 2 (Figure 6*b*). Lava plains in the vicinity of Tharsis have been estimated to be at least 500 m thick [*DeHon*, 1985] and locally may be much thicker. The additional insulation provided by the emplacement of 500 m of lava over the original frozen surface caused the melting isotherm at the base of the permafrost layer to rise until local thermal equilibrium was reestablished. Since the thermal conductivities of ice and basalt are similar, the net upward displacement of the melting isotherm should have been comparable to the lava thickness (Figure 6*c*), leading to melting of 1.5 to 2 km of permafrost. *Tanaka and Chapman* [1990] estimate the area of the possible aquifer zone for Mangala Valles at 10^5 km^2, but the area affected by Tharsis could easily be an order of magnitude greater. If the porosity of the region is assumed to be 10% [*MacKinnon and Tanaka*, 1989], then the total volume of water available to the Mangala Valles system may have been 2×10^{13} to 2×10^{14} m^3, depending on the actual areal extent. Either estimate is clearly sufficient to supply the 5×10^{12} m^3 minimum estimate of the total water discharge through Mangala Valles [*Tanaka and Chapman*, 1990].

Flow of water eventually developed integrated channel systems. Continued damming by ice, perhaps aided by cyclic release of water associated with sporadic volcanism in the source area, resulted in episodic channel cutting leaving terraces in some places [*Chapman and Tanaka*, 1992]. The inferred rapid release of water, deep erosion of older terrain, and creation of local lakes behind ice dams and their subsequent release were conducive to the development of the braided channel observed in the lower reaches of Mangala Valles [*Tanaka and Chapman*, 1990]. Channels clogged with sediments may also have contained pockets of ice. As the stranded ice melted or ablated, suffusion may have produced the pitted and disrupted terrain seen along isolated segments of the channel floor (Figure 7), similar to features observed around channels elsewhere on Mars [*Costard*, 1989]. Alternatively, cavitation during the highest flow levels may have enlarged existing depressions on the channel floor.

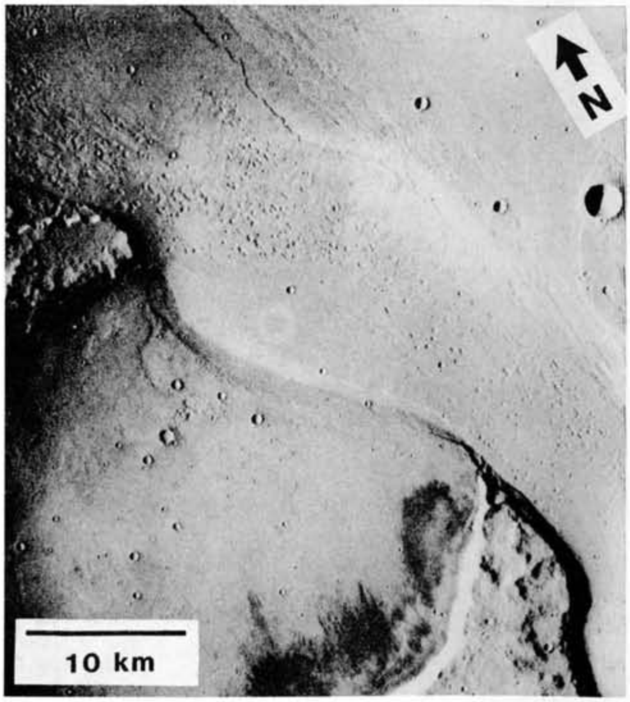

Fig. 7. Pitted floor materials in the proximal reaches of the Mangala Valles main channel. Pitting may result from stranded blocks of ice or cavitation during highest flow levels. Viking frame 448S36, centered at 13°S, 150.5°W.

DISCUSSION

Release of volatiles. The geometry of the Mangala Valles channel near its source provides constraints on the possible fluid discharge through the channel system. *Komar* [1979] estimated the discharge through part of the distal Mangala Valles to be between 10^6 and 10^7 m^3/s for flow depths between 10 and 100 m. These discharge estimates are two orders of magnitude smaller than that of the Kasai Valles flood [*Robinson and Tanaka*, 1990], but they are consistent with the maximum discharge of 9.1×10^6 m^3/s for the Lake Missoula flood determined at Wallula Gap [*Baker*, 1978]. For comparison, it should be noted that the average discharge of the Amazon River is 1.8×10^5 m^3/s, which accounts for 20% of the water discharged by all terrestrial rivers [*Baker*, 1987]. *Tanaka and Chapman* [1990] used Komar's discharge estimates to constrain the minimum total water discharge through the entire Mangala Valles channel system to be 5×10^{12} m^3, resulting in total flood durations of from 6 to 60 days.

The geometry of the 5-km-wide breach at the source graben provides information about the fluid flow under such conditions (Table 1). The bottom shear stress at Mangala Valles was much smaller than the 1800 N m^2 calculated for the catastrophic flood event at Kasei Valles [*Robinson and Tanaka*, 1990]. Consequently, the Mangala Valles floods were probably far less erosive than the high discharge Kasei Valles flood. Reduced erosion helps explain how the confined source breach could survive prolonged water discharge without becoming enlarged beyond its present width.

A related issue is the permeability required to deliver sufficient water to the source graben to maintain the calculated discharge rates. Unlike other outflow channels that head in a region of chaotic terrain [e.g., *Carr*, 1979], Mangala Valles lacks an obvious catchment basin near the source graben in which to accumulate a large volume of water. Consequently, in order for the water to be delivered to the source graben rapidly enough to maintain a discharge rate of

TABLE 1. Flow Conditions Through the Source Channel of the Mangala Valles at the Breached Graben

Depth, m	Velocity, m/s	Discharge, m^3/s	Bottom Shear Stress, $N\,m^2$	Duration,* days
119	18.5	10^7	310	6
30	7.4	10^6	49	58
7.5	2.9	10^5	8	580
1.9	1.2	10^4	1	5800

Calculations are based on a breach 5 km wide, 900 m high, with walls sloping 45° to the floor. Equations used are from *Robinson and Tanaka* [1990], with bed slope of 0.001 and Manning *n* of 0.025.
*Flow duration is based upon an estimated total discharge for the Mangala Valles system of 5×10^{12} m^3 [*Tanaka and Chapman*, 1990].

up to 10^7 m^3/s, any aquifer system must have a very high hydraulic conductivity.

Permeable basalt has a hydraulic conductivity of 10^{-2} to 10^{-7} m/s, equivalent to permeabilities of 10^3 to 10^{-2} darcies [*Freeze and Cherry*, 1979, p. 29]. Assuming that the breached Memnonia Fossae graben is an extremely efficient conduit for transporting water from the aquifer to the channel head area, Darcy's law provides a way to quantify the rate of water release into the graben (Table 2). *Tanaka and Chapman* [1990] consider the source graben to be up to 1500 km in length, partially buried by lava flows from the Tharsis volcanoes, so we considered graben lengths bracketing this value. The average topographic gradient on the western flank of the Tharsis Rise is 0.002 within 1000 km of Mangala Valles [*U.S. Geological Survey*, 1989], but it increases to 0.004 for a distance up to 1500 km from the channel system [*Tanaka and Chapman*, 1990]. If the aquifer discharged water through both walls of the graben, the values in Table 2 would be doubled, but even then the maximum input of water into the graben would be 1.6×10^5 m^3/s. In addition, as water leaves the aquifer, the water table around the graben will be drawn down, further decreasing the outflow rate from the aquifer as a whole [*Freeze and Cherry*, 1979, pp. 488-489].

It seems unlikely that tens of thousands of square kilometers around the graben would fortuitously have an average hydraulic conductivity beyond the top end of the range observed for terrestrial volcanic materials. Consequently, the rate of aquifer supply to the source graben may have been much less than 10^5 m^3/s. Realized discharge rates into the source breach may have been more in the range of 10^3 m^3/s, resulting in the prolonged release of a relatively shallow flow over hundreds to thousands of days. The large volume of available meltwater estimated from considerations of heat flow could extend the duration of a low discharge release into the Mangala Valles system to centuries or even millenia. Such long discharge durations raise the possibility that Mangala Valles may have less of a "catastrophic" origin than is currently acknowledged.

Factors influencing the release of volatiles. The sequence of events involved in the formation of Mangala Valles illustrates how structural elements in the region, such as the large faults and grabens and the inferred rotated fault block near the source graben, profoundly influenced the migration of volatiles. The location of Mangala Valles was controlled by ancient north-south oriented faults associated with grabens radial to the Tharsis Rise. These structures created barriers to the emplacement of plains units (both volcanic and fluvial in origin) and either enhanced or hindered the migration of subsurface volatiles. Structurally defined segments of the Martian crust became the primary building blocks for subsequent modification by volcanic and fluvial processes.

TABLE 2. Calculated Discharge Rate Through One Wall of the Memnonia Fossae Graben From a Surrounding Aquifer

Graben Length m	Hydraulic Gradient	Hydraulic Conductivity* m/s	Discharge m^3/s
10^6	-2×10^{-3}	10^{-2}	2×10^4
10^6	-2×10^{-3}	10^{-7}	2×10^{-1}
10^6	-4×10^{-3}	10^{-2}	4×10^4
10^6	-4×10^{-3}	10^{-7}	4×10^{-1}
2×10^6	-2×10^{-3}	10^{-2}	4×10^4
2×10^6	-2×10^{-3}	10^{-7}	4×10^{-1}
2×10^6	-4×10^{-3}	10^{-2}	8×10^4
2×10^6	-4×10^{-3}	10^{-7}	8×10^{-1}

Calculations are from Darcy's law, assuming a uniform height of 1 km for the aquifer [after *Tanaka and Chapman*, 1990].
*Hydraulic conductivities of 10^{-2} to 10^{-7} correspond to permeabilities of 10^3 to 10^{-2} darcies, the range encountered in terrestrial permeable basalt [*Freeze and Cherry*, 1979, p. 29].

Mangala Valles is a striking example of the complex history which can develop when the interplay of tectonism, volcanism, and volatile migration acts on a localized region on Mars.

The southern reaches of Mangala Valles display distinct orientations of channel erosion and deposition (i.e., streamlined islands) which may be the result of either nonuniform drainage following a single flooding event or perhaps they may reflect multiple episodes of flooding and erosion. Conclusive evidence for multiple flood episodes is lacking in the units preserved along the southern reaches of Mangala Valles, but two distinct episodes of flooding and erosion have been inferred from deposits in the northern reaches of Mangala Valles [*Tanaka and Chapman*, 1990]. The latest flooding event scoured a channel along the topographic low between cratered plains to the east and early channel materials to the west, with a near-source gradient of 0.001 displayed in topography from Earth-based radar measurements [*Zimbelman*, 1989*a*]. Densely cratered material may serve as a limited aquifer to supply at least some water into the channel system from the west through the eastward dipping cratered plains, but the amount of water available from this source is constrained by a broad topographic low along longitude 160°W (Figure 1), placing a firm limit to any westward trending aquifer.

The association of volcanic plains with the channel deposits implies volcanism may have been important in both the initiation of volatile release and in the migration of volatiles to the source area. Volcanic plains emanating from source areas on or near the faulted highland materials near Mangala Valles raise the possibility that subsurface volcanic activity could have provided the "trigger" mechanism for the initial release of water. The simplest scenario would involve intrusion of magma at depth, initiating the release of water, followed by eruption of volcanic plains as the magma eventually reached the surface. In this case, the Hp plains would represent the surface expression of the magma that initiated the early channelling episode of *Tanaka and Chapman* [1990], with the Ad plains corresponding to a subsequent outbreak episode. A variation on this theme could have the volatile release of the early channel episode emanating from a source graben north of Memnonia Fossae, such as a subdued graben near 12°S, 148°W (Figure 1), with the magma reaching the surface further south to form the Hp plains. The source area for this early water release would then be completely buried by the Hp plains and channel deposits.

Although this scenario for the interplay of volatiles and surface materials is presently speculative in nature, it is consistent with both the regional geological history and with observations of surface features associated with Mangala Valles. The high-resolution images planned as part of the Mars Observer and Mars 94 missions will be capable of revealing details related to the channel formation process, such as boulder size and the degree of bedrock scour, which could provide a test of the various volatile sources discussed above.

CONCLUSIONS

1. The Mangala Valles channel system is different from other Martian outflow channels in that they emanate from a point source determined by the local interplay of tectonism, volcanism, and volatiles which led directly to the release of groundwater.

2. Water discharge rates through the southern reaches of Mangala Valles may have been substantially less than estimates derived from the canyon system as a whole, indicating that the accumulation and release of water may have been more prolonged than previously envisioned.

3. The sequence of events derived from mapping of units along the southern reaches of Mangala Valles is closely related to the structures present in the area.

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R.A. Craddock and J.R. Zimbelman, CEPS/NASM, MRC 315, Smithsonian Institution, Washington, DC 20560.
R. Greeley, Department of Geology, Arizona State University, Tempe, AZ 85287-1404.
R.O. Kuzmin, Vernadsky Institute, Russian Academy of Sciences, 117975, V-33Y GSP-I Kosygin St. 19, Moscow, Russia.

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