Published in final edited form as:

Icarus. 2015 January 1; 245: 333–347. doi:10.1016/j.icarus.2014.09.040.

Episodes of fluvial and volcanic activity in Mangala Valles, Mars

Amber L. Keske^{a,*}, Christopher W. Hamilton^b, Alfred S. McEwen^b, and Ingrid J. Daubar^b

^aSchool of Earth and Space Exploration, Arizona State University, 201 E. Orange Mall, Tempe, AZ 85287, United States

^bLunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, United States

Abstract

A new mapping-based study of the 900-km-long Mangala Valles outflow system was motivated by the availability of new high-resolution images and continued debates about the roles of water and lava in outflow channels on Mars. This study uses photogeologic analysis, geomorphic surface mapping, cratering statistics, and relative stratigraphy. Results show that Mangala Valles underwent at least two episodes of fluvial activity and at least three episodes of volcanic activity during the Late Amazonian. The occurrence of scoured bedrock at the base of the mapped stratigraphy, in addition to evidence provided by crater retention ages, suggests that fluvial activity preceded the deposition of two of the volcanic units. Crater counts performed at 30 locations throughout the area have allowed us to construct the following timeline: (1) formation of Noachian Highlands and possible initial flooding event(s) before ~1 Ga, (2) emplacement of Tharsis lava flows in the valley from ~700 to 1000 Ma, (3) a megaflooding event at ~700–800 Ma sourced from Mangala Fossa, (4) valley fill by a sequence of lava flows sourced from Mangala Fossa ~400–500 Ma, (5) another megaflooding event from ~400 Ma, (6) a final phase of volcanism sourced from Mangala Fossa ~300–350 Ma, and (7) emplacement of eolian sedimentary deposits in the northern portion of the valley ~300 Ma. These results are consistent with alternating episodes of aqueous flooding and volcanism in the valles. This pattern of geologic activity is similar to that of other outflow systems, such as Kasei Valles, suggesting that there is a recurring, and perhaps coupled, nature of these processes on Mars.

Keywords

Mars; surface; Volcanism; Geological processes

1. Introduction

The origin and relationships between major Amazonian-age fluvial outflow systems on Mars is a subject of ongoing debate. In particular, there are challenges associated with generating the substantial volumes of water required to erode and transport material out of these systems, which has prompted a wide range of alternative formation hypotheses including aqueous flooding (e.g., Baker and Milton, 1974; Sharp and Malin, 1975), volcanism (e.g., Leverington, 2004), glacial erosion (e.g., Lucchitta, 1982), eolian erosion (e.g., Cutts and

*Corresponding author. alkeske@asu.edu (A.L. Keske).

Blasius, 1981), debris flows (e.g., Nummedal and Prior, 1981), or a combination of these processes (e.g., Chapman et al., 2003, 2010; Warner et al., 2009; McEwen et al., 2012). While lack of terrestrial analogs of comparable scale and complexity renders geomorphic comparison of large landscape features in these regions difficult (Mars Channel Working Group, 1983), new high-resolution images allow us to identify smaller surface features that provide clues about the processes that have influenced their overall surface geomorphology, allowing for reconstruction of their activity history. Moreover, relative placement of outflow processes within the martian global chronology contributes to constraints on global climate models and an understanding of how the martian subsurface has changed through time. Mangala Valles serves as an ideal case study due to its relative isolation from the influence of additional outflow regions, rendering it the best-known example of a relatively closed outflow system on Mars.

Mangala Valles is a 900-km-long north–south trending system of channels and wide valleys southwest of the Tharsis rise, about 800 km south of the equator (Fig. 1). It heads at Mangala Fossa, a 200-km-long graben that is part of the Memnonia Fossae graben system. It is about 5–7 km wide at the mouth, and gradually opens to the north for about 300 km, where it then broadens and loses much of its topographic variation (Fig. 2). At its widest, Mangala Valles is about 200 km across, north of which it transitions into three narrow channels that drain into Amazonis Planitia. Near its source and in northwestern channel segments, the topographic relief between the channel floors and adjacent plateaus reaches up to 150 m, whereas the broad, middle portion of the system exhibits a rather smooth transition from a topographic low running along its western margin to a topographic high on the eastern side, which is dominated by a high plateau. Mangala Valles is located near the western boundary of the Tharsis volcanic plains with the cratered highlands and is surrounded by heavily cratered Noachian Highlands, which includes a narrow mountain range on the eastern side of Mangala Valles that separates it from smooth plains of the Tharsis Montes Formation.

Mangala Valles has been mapped previously, but these maps focus on smaller areas (Chapman et al., 1989a,b,c, 1991; Chapman and Tanaka, 1993; Tanaka and Chapman, 1990; Craddock and Greeley, 1994; Zimbelman et al., 1994; Basilevsky et al., 2008) and/or are less detailed (Tanaka and Chapman, 1990; Ghatan et al., 2005) due to the use of lower-resolution images. The first objective of this study is to map the Mangala Valles using Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) images (Malin et al., 2007) to achieve a level of detail comparable to Basilevsky et al. (2008), but over the outflow channel system in its entirety. CTX images provide a spatial resolution (~6 m/pixel) and coverage that was not available to previous authors, who relied on High-Resolution Stereo Camera (HRSC) onboard Mars Express (Jaumann et al., 2007), Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) (Malin and Edgett, 2001), MGS Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 2001), and Viking data (Carr et al., 1972). The resolution of CTX images allows for the detection of small, but key surface features that lead to an improved understanding of the stratigraphic relations of larger geologic units. Our second objective is to use the map along with crater counts and additional photogeologic observations of relative stratigraphy to determine the probable sequence of events that led to the present appearance of the system, and to draw comparisons to other martian outflow systems. This study does

not include quantitative modeling of the source mechanism nor of erosive flooding events in Mangala Valles; for modeling approaches the reader is referred to Wilson and Head (2002), Thakur et al. (2007), Wilson et al. (2009), Bargery and Wilson (2011), and references therein.

2. Methods

The mapping area extends from roughly 3.5°S to 20°S and 214°E to 203°E, covering a region that is about 925 km in length by 625 km in width. Digital mapping was performed using an image mosaic base layer consisting of daytime infrared images acquired from the Mars Odyssey Thermal Emission Imaging System (THEMIS) instrument (Christensen et al., 2004), with a spatial resolution of 100 m/pixel (Edwards et al., 2011; Hill et al., 2014). Individual CTX images were used for detailed mapping and analysis due to their relatively high resolution (~6 m/pixel), near-ideal illumination conditions (~3 PM), and excellent coverage of the mapping area. Images from the MRO High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007), which have a scale of 0.3 m/pixel, were also used, though to a lesser extent than CTX because they have very limited spatial coverage in this region. Gridded elevation data from the MOLA instrument (Smith et al., 2001) was used in the forms of contours, elevation cross sections, and colorized elevation to help identify unit contacts and perform other detailed analyses. Similarly, Digital Terrain Models (DTMs) from the HRSC (Jaumann et al., 2007) (~12.5 m/pixel) were useful in determining elevation differences for geologic mapping. All elevations discussed are based on gridded MOLA elevation values, and map coordinates use the IAU2000 reference system. Geologic maps from previous work (Chapman et al., 1989a,b,c, 1991; Chapman and Tanaka, 1993; Tanaka and Chapman, 1990; Craddock and Greeley, 1994; Zimbelman et al., 1994; Basilevsky et al., 2008) were also used as mapping references. The map units in this study were defined using surface geomorphology alone. Therefore, the map presented is not an interpretive bedrock map, but rather a map of surface features observable in visible high-resolution images. Following correlation and geomorphic characterization, all major geologic units, as well as specific locales of interest, were dated using standard crater counting techniques (as described by Michael and Neukum, 2010). Rectangular areas of ~60–400 km² were outlined on CTX images and all craters larger than ~50 m in diameter were counted within the area. Since model age uncertainty increases with decreasing area counted, small features (e.g., streamlined islands) were not dated. The resulting size frequency distributions were plotted with $\sqrt{2}$ diameter binning and model ages were fitted using the chronology and production functions derived in Hartmann (2005) using the Craterstats2 program (Michael and Neukum, 2010). The number of crater diameter bins used to calculate crater retention ages was chosen on a case-by-case basis based on where the minimum bin unaffected by rollover due to the CTX image resolution limit and the maximum bin unaffected by older resurfacing events occur on each plot. Due to the expectation that many of the surfaces counted underwent one or more resurfacing episodes, differential fits were used as they are more appropriate for fitting multiple resurfacing events (Michael, 2013), which are expressed when an older isochron can be identified in the larger crater bins. Note that crater counting uncertainties are a multivariable statistical description of how well the mean is known based on the number and distribution of samples in the individual crater count and should not be interpreted as the

uncertainty of the absolute age determined by the crater count. Additionally, the ages calculated represent the time estimate of surface modification, not necessarily the time of bedrock emplacement.

3. Results

Fig. 3 shows our map of the Mangala Valles region and includes 19 units. The detailed mapping is focused within the confines of the main valley walls with surrounding geologic units defined in accord with the current global geologic map for Mars (Tanaka et al., 2014). Note that all Noachian highland geologic units are shown as one encompassing unit, Nh. Since crater rim and ejecta materials within Nh are apparently not related to major resurfacing events in Mangala Valles, they have not been included on the maps. A detail of the southern portion of the mapping area is provided in Fig. 4, and a detail of the mapped northwestern channels is provided in Fig. 5.

3.1. Mapped geomorphologies

3.1.1. Rough terrain (Hrt)—This unit refers to regions with hummocky, high-relief surfaces that retain high crater densities, yet are distinguishable from unmodified highland terrain by evidence of partial resurfacing and relatively shallow slopes. It is present in much of the northern portion of the study area and in the high-elevation areas surrounding the main valley. Within the main valley and throughout the northern and northwestern channels, Hrt surfaces often manifest as small islands between or within larger geological units and tend to sit higher than the surroundings, with elevations approaching 500 m (Fig. 6).

3.1.2. Smooth plain 1 (Asp1)—Asp1 is located in the northeastern portion of the main valley, representing a topographic high within the valley with elevations increasing from 100 m to 450 m toward the northeast. Asp1 is considered a smooth plain due to this relative lack of topographic variation, though it exhibits higher textural variation than the other smooth plains units. Lobes, sinuous channels, pits, hummocky plains, plates, and embayed and infilled impact craters can be identified throughout its landscape (Fig. 7). Its western flank is completely bounded by Hrt, which also appear as embayed islands within Asp1. Similarly, the north and northeastern portions are bounded by highland terrain. To the south, Asp2 stratigraphically overlies Asp1. At its easternmost flank, Asp1 continues southward and is continuous with the topographically higher geologic unit AHv, which shares its geomorphology and crater densities (Fig. 15).

3.1.3. Scoured terrain (Ast)—The scoured terrain morphology is one of the most prevalent units in Mangala Valles. Its southern reach begins at the valley mouth as two exposures flanking a central deposit of Asp3 to the west and east. However, the bulk of Ast begins about 100 km northwest of the valley opening and continues northward along the western-central area of the main valley, with a general decrease in elevation from –50 m to –950 m. At the northwest of the main valley, it branches off into three distinctive channel sub-networks, reaching an elevation low of about –2800 m. The geomorphology of Ast is characterized by subparallel linear grooves between sharp ridges that often circumvent obstacles, cut through highland bedrock, and superpose other valley geomorphologies (Fig.

8B). Ast is largely composed of vast networks of anastomosing channels, and knobbed streamlined islands are scattered throughout its central body (Fig. 9). Benches and horizontal terraces are present on confining walls throughout the unit (Fig. 8A).

3.1.4. Large knobbed (Alk)—Alk refers to rounded or plateaued islands with teardrop-shaped bars that occur within the main central body and in the northwestern channel network of Ast (Fig. 9). Most plateaued knobs are between 150 and 300 m in height, while the more rounded knobs tend to be less than 150 m in height. The stepped/terraced topographic profile of these landforms suggests that these features more likely represent streamlined erosion of layered bedrock rather than depositional bars (Baker and Kochel, 1979; Milton, 1974; Greeley et al., 1977).

3.1.5. Smooth plain 2 (Asp2)—Comprising the majority of the southeastern and middle portion of the valley, Asp2 is one of the largest and most distinctive units in the valley. Its southern portion is quite flat, with only 90 m of relief between 17°S and 13°S. North of this area, it begins to dramatically decrease in elevation, reaching a low of about –200 m within the valley at 10°S. While the bulk of it is confined to the valley, it is scattered throughout the northwestern channels in disconnected islands of inverted topography (Fig. 10C), whose surfaces steadily decrease in elevation northward to a minimum of –1800 m at 4.5°S. It is smooth and flat, and tends to be platy on both small and large scales. It exhibits large crater embayment and infill features, some lobate margins (Fig. 10A), and streamlined features (Fig. 10D). There is less internal variation than is observed in Asp1, though there is a general increase in heterogeneity northward within the unit. Perhaps the most interesting characteristic of Asp2 is its broken-up appearance (Fig. 10C). Sections of it can be identified as residual islands at a distance from the bulk of the unit throughout the valley, but most notably in the southern valley region and in the northwestern channels. Many of these islands, as well as the edges of the main plateau, are heavily scoured with channels and gullies that are oriented in a general northwesterly direction.

3.1.6. Grooved slope (Ags)—These features are transitional from Asp2 to Ast, mapped in multiple locations along the western and northern flanks and in the interior of Asp2. At the western margin of Asp2, these deep, subparallel grooves tend to originate with ridge orientations perpendicular to the orientation of the margin of Asp2—where trough heads break up the edges of the plateau and form complex multitudes of narrow canyons—then curve to the north until they are aligned with the ridges of Ast immediately to the west (Fig. 10B). Exposures that begin in the interior of Asp2 are northwest-trending. Beginning at about (211°S, 16°S) on the interior of the Asp2 plateau, a wide, shallow trough approximately 27 km in length and 3.5 km in width cuts into the bedrock and extends toward the edge of the plateau (Fig. 10E). Within the trough are scattered dissected, scoured pieces of residual Asp2 material. A similar feature can be found wrapped around a large mid-valley pedestal crater interfacing with the plateau (Fig. 11). This deeply incised canyon begins at the south of the crater and debouches at the north, where the ridge orientation rejoins Ast ridges. Again, scoured islands of Asp2 are distributed throughout the trough, and smaller troughs to the south and east of the unit open into the main canyon.

3.1.7. Polygonal blocked (Apb)—Apb terrain was mapped in the southern valley and in the northwestern channels, appearing as lower, subdivided smooth blocks with dissecting canyons near the edges of Asp2 and Ats (Fig. 12A). The polygons range in size from ~300 m to 3 km in width.

3.1.8. Small knobbed (Ask)—Ask features appear in the southern portion of the valley and in the northwestern channels in small batches adjacent to Apb, Ats, and Asp3. They are rounder, more widely spaced, and generally more uniform in size than Apb, and range from 50 to 1500 m across. Ask is embayed by Asp3 in the southern valley (Fig. 12B).

3.1.9. Terraced scoured (Ats)—The Ats unit occurs predominantly in the southern portion of Mangala Valles, as well as within elongate islands along the western edge of the valley within Asp3. It bears a general scoured or etched appearance, with deep linear grooves and steep walls (Fig. 12C), and is confined to isolated high islands and terraces often capped by a small piece of Asp2.

3.1.10. Smooth plain 3 (Asp3)—Asp3 begins at Mangala Fossa, covering the entire floor of the fossa as well as the valley opening, and follows the topographic gradient along the west valley wall, into the easternmost northwestern channel, and out onto the flat channel debouchment surface. It begins at about –140 m elevation, increases mid-valley to –90 m, and then gradually decreases in elevation toward the north, terminating at a low of –2800 m in the outlet area. Its floor is smooth with few craters, its edges are lobate in appearance, and it embays islands and large craters. Despite being relatively low in relief, there is significant heterogeneity within the unit. Lobes appear within the unit, sometimes in narrow, sinuous landforms (Fig. 13A), and small meandering channels appear at the valley mouth (Fig. 13B). One notable characteristic of this unit are shallow pits ~300–400 m in diameter with flat, soft rims that appear all throughout Asp3, but are most abundant in the middle and northern portion of the unit (Fig. 13C). These unusual features are most often circular, but many appear elongated or coalesced. At the contact between Asp3 and the Ast unit, the ridges on the Ast unit often abruptly terminate where the outer lobe of Asp3 begins (Fig. 13A and E).

3.1.11. Smooth plain 4 (Asp4)—Asp4 begins in the northern portion of the main valley where it divides into two branches that continue northward. It is extremely flat in its southern reach (elevation ranges from about –75 m to –100 m), with indistinct, flat interior lobes and muted craters (Fig. 14A). There is extensive eolian activity and a thick dust mantle, which appears to have buried most craters below ~500 m in diameter. The northern branches of Asp4 include additional muted features, including small, shallow islands (Fig. 14B); however, the mantle appears to be somewhat thinner in the western branch and thinnest in the eastern branch. The elevation within these branches steadily decreases from about –100 m to –2300 m, where they transition to amphitheater-headed canyons that debouch onto the IHt unit.

3.2. Crater counts

Crater counts were performed in 30 locations throughout the area (Table 1) (see Supplementary materials for map of areas counted and for individual size frequency distribution plots). Dating using crater counts introduces the question of what is being dated. A thin veneer of volcanic resurfacing will not erase larger craters from the underlying surface, so only the smaller diameter bins will reflect the younger age. Determining the age of a fluvially resurfaced area is also problematic in that, unlike volcanic resurfacing, the craters may be eroded rather than mantled. While it may be evident that crater erasure has occurred, many craters may appear only partially erased, making the distinction between craters erased by fluvial processes and younger eolian processes unclear. This ambiguity additionally complicates attempts to date surfaces that have undergone multiple fluvial resurfacing events. The distinction between sudden resurfacing events such as a single destructive flood and ongoing long-term processes such as eolian erasure can also be difficult to distinguish in crater size frequency distributions. For these reasons, crater retention age is not as much a measurement of absolute age of the rocks themselves as it is a measure of the crater survival age, the uncertainty of which is very difficult to quantify. Thus, interpretations must be supplemented with geologic observations (Hartmann, 2005; Michael, 2013) (Table 2).

According to the model ages derived from these crater counts, Hrt surfaces are the oldest (average 3680 ± 25 Ma) in the valley, units Asp1 (average 878 ± 66 Ma) and Ast (average 775 ± 64 Ma) are intermediate in age, and Asp2 (average 434 ± 37 Ma), Asp3 (average 346 ± 41 Ma), and Asp4 (average 330 ± 36 Ma) are the youngest. Small differences in model ages between sample areas with overlapping error bars within the same geomorphic unit (e.g., sample areas 11 and 12 within Asp2) likely represent variations due to statistical errors inherent in crater counting rather than real age variations. However, model ages within the same geomorphic unit exhibiting error bars that do not overlap, as is the case with sample areas 20 and 21 in unit Asp1, more likely represent separate events that resulted in similar geomorphologies. Of the units in which crater counts were performed, Asp4 was the most difficult to date where a thick dusty mantle covered small craters, resulting in a shallowly sloped crater size-frequency distribution (SFD) due to the strong sample bias toward larger craters. Thus, errors in the model ages for Asp4 may be larger than the formal uncertainties.

4. Discussion

Large channel landforms in major outflow regions on Mars such as Kasei, Ares, Tiu, Simund, Maja, and Mangala Valles have been compared to the channeled scablands of the Pacific Northwest, leading to general acceptance that these valleys were carved by water during megaflooding events (e.g., McCauley et al., 1972; Baker and Milton, 1974; Sharp and Malin, 1975; Komar, 1979; Burr et al., 2009; Carr and Head, 2010). However, identification of volcanic deposits on the channel floors in some of these regions have led to an alternative hypothesis suggesting that large martian outflow regions such as Mangala Valles were instead carved by vast volumes of lava (Leverington, 2007). Alternate hypotheses for Mangala Valles include the exposure of previously buried volcanic material by flooding (Zimbelman et al., 1992; Ghatan et al., 2005), fluvial activity followed by glacial activity

(Head et al., 2004), volcanic deposition following megaflooding events (e.g., McEwen et al., 2012), and intermittent volcanism between flooding events (e.g., Chapman and Tanaka, 1990, 1993; Tanaka and Chapman, 1990).

4.1. Evidence of fluvial activity

In Mangala Valles, we have observed numerous landforms characteristic of fluid flow including streamlined features (Figs. 8A, 9, 10C, and 11), ridged topography aligned parallel to confining unit walls (Figs. 8 and 9B), downcutting of steep slopes (Figs. 8B and 19), networks of braided channels, pendent bars (Fig. 9), cutbank walls (Figs. 8C and 9B), cataracts (Figs. 8A, 10E, and 11), channel terraces (Fig. 8A and C), and amphitheater-headed canyons (Fig. 16A). Pre-fluvial impact craters on fluvial surfaces are observed to have an eroded, rather than covered or filled appearance, with lower, subdued rims. The resemblance of deep longitudinal striae within the Ast unit to Channeled Scabland grooves is suggestive of bedrock erosion by longitudinal roller vortices in powerful floodwaters (McCauley et al., 1972; Baker, 1973; Sharp and Malin, 1975). We consider the features of Ats to be the result of fluvial erosion, and are likely channel terraces and partially eroded topographic highs derived from the same event or events as scoured terrain, since these landforms often grade smoothly down into another fluvial unit of matching flow ridge orientation. Similar arguments apply for Ags features. While there is evidence that turbulent lava flows are locally capable of producing land-forms traditionally associated with fluvial activity (e.g., Baker et al., 1992), a well-accepted example of a large lava-carved feature on Mars has yet to be conclusively identified, making a fluvial interpretation more favorable. However, large lava-carved channels have been purported on Mercury (Byrne et al., 2013).

4.2. Evidence of volcanic activity

Within the smooth plains units, we have observed features typical of volcanic landforms such as lobate-margined flow fronts (Figs. 10A, 13A and E), ridged flows (Fig. 17A), collapse pits (Fig. 17B), and embayed landforms (Figs. 7A, B, 12B, 13A and B). Compared to Ast, smooth plains units have relatively few flow features, the exceptions being sinuous channels and aggradational streamlined features similar to those observed in Kasei Valles (Chapman et al., 2010) (Fig. 10D). Older craters with high rims tend to be embayed by what we interpret to be lava flows, whereas smaller craters have a characteristic infilled appearance. This would occur when the thickness of the lava flow exceeds the height of the crater rim and/or breaches it. An infilled appearance can also result if a portion of the crater rim wall is collapsed, allowing for flooding of the crater floor with lava (Fig. 7B). Post-lava-emplacement impact craters tend to be accompanied by blocky ejecta, indicative of mechanically resistant bedrock (Basilevsky et al., 2008). The shallow pits observed as part of the Asp3 unit were previously interpreted as thermokarst pits that formed when subsurface ice was exposed and subsequently sublimated during volatile flooding (Chapman and Tanaka, 1993; Levy and Head, 2005). However, we suggest the alternative hypothesis that they are lava-rise pits (Walker, 1991), which formed when lava encountered obstacles on the underlying surface. This would have forced the lava around the high-standing obstacles, leading to local topographic inversions and the formation of shallow, oblong pits as the surrounding lava thickened by inflation. Morphological features such as these pits and smooth ridges within the unit are interpreted to be the result of lava draping ridged

topography, most evident in exposures of older ridges of Ast adjacent to muted ridged landforms within Asp3 of matching size and orientation (Fig. 13D). The expression of underlying topography suggests a relatively thin and fluid, probably basaltic, lava flow. The geomorphology of Asp1, on the other hand, is more pronounced than that of Asp3, having the hummocky, inflated, rafted appearance of similar to terrestrial inflated pahoehoe basalt surface morphology (see Keszthelyi et al., 2000, 2004).

Asp2 is characterized by sheet-like, homogeneous surfaces devoid of inflation features or expression of any underlying topographic features, resembling more closely lunar mare lavas or Archean high-Mg basalts on Earth, which are believed to be assemblages of fluid lava flows (Head, 1976). Asp4 is similarly homogeneous. Though much of its surface is coated in a fine mantle that obscures most of its features, it has an erosional pattern suggesting poorly consolidated material. Two candidate hypotheses arise for these observations: (1) it is a locally derived tephra deposit whose relatively soft bedrock is easily eroded and reworked, allowing for development of a large dune field at the surface, or (2) it is a more distally sourced, unconsolidated tephra deposit that has been transported from the Upper Member Medusae Fossae Formation to the north.

4.3. Evidence of post-emplacement fluvial modification of volcanic units

While most of the smooth plains units show evidence of only eolian and impact modification, there are numerous features within Asp2 suggesting that it has undergone fluvial modification. Many of the crater rims have been eroded and flattened (Fig. 11), islands of Hrt and large craters within the unit are outlined in deep trenches (Fig. 11), large outcrops of inverted topography are present on its surface and along its flanks surrounded by Ast floor morphologies (Fig. 10B), and intact buttes whose heights correlate with that of the Asp2 plateau edge are scattered throughout the valley. Wide, shallow trenches marked by the Ags geomorphology with knickpoints occurring near the center of the plateau as well as on its flanks, and subtle, superficial streaks throughout the Asp2 unit seem to suggest overland flow and powerful bedrock abrasion (Fig. 16). Furthermore, the geometry of small amphitheater-headed canyons along its margin (Fig. 16C) is analogous to the terrestrial canyons carved in basaltic bedrock by megaflood overland flow (Lamb et al., 2008). These features exist at a smaller scale in Asp4 as well, which hosts amphitheater-headed canyons and streamlined islands (Fig. 14B) underneath its mantle.

Most notably in the northwestern channels and the southern valley region, remnant buttes and islands of Asp2 tend to be proximal to Ats, Apb, and Ask units. The Ats unit primarily occurs around islands of Asp2 material and is interpreted to be the result of partial erosion of segments of Asp2. Apb morphologies, which tend to occur at the edges of Asp2, often dividing the interface between Asp2 and Ask, may also represent partially eroded Asp2 material, and Ask more extensively eroded Asp2 material. This hypothesis is supported where transitional phases between Asp2, Apb, and Ask are visible (Fig. 12D). The mechanism for differing Ats and Apb morphologies is unclear, but we speculate that it is related to bedrock heterogeneities. See Fig. 18 for interpretive bedrock modification map.

4.4. Geological history

The overall geologic interpretation of these units is largely dependent on their relative ages and stratigraphic relationships. Aside from Hrt and Asp1, the oldest ages are attributed to Ast, though high numerical errors and a significant spread of individual ages support a multi-event flooding hypothesis, assuming these floods did not resurface the entire area uniformly. Moreover, we cannot rule out possible fluvial events during the ~1–3 Ga period because the crater retention ages of these surfaces have been reset by younger lava deposits or fluvial activity. While this information alone is not necessarily significant, when combined with observations of the fluvial modification of volcanic units, a basic timeline involving periods of flooding alternating with periods of volcanism can be inferred.

Aside from Hrt, crater counts designate Asp1 as having the oldest valley surfaces (~700–950 Ma), the ages of which overlap with some of the oldest Ast ages, making it unclear whether any or all of the originating volcanic events depositing Asp1 material predate or postdate fluvial activity. Since it stratigraphically underlies Asp2, its southern subsurface extent is unknown. Asp3 is the youngest volcanic flow unit, as evidenced by its stratigraphic position above all other valley geologic units besides Asp4 and its relatively young crater retention ages (300–400 Ma). Interestingly, Asp3 age estimates overlap with those of Asp2, though Asp2 ages may be underestimated since there may have been partial resurfacing due to post-depositional fluvial activity. Asp4 has the youngest average crater retention age (~300 Ma), though the individual ages increase with decreasing mantle thickness, suggesting a greater influence of the underlying bedrock on the crater retention ages where the mantle is thin. This renders stratigraphic placement of both the surface material and the underlying bedrock difficult, since there are few clues to the origin of the mantle in photogeologic analysis, and the crater retention ages are somewhat unreliable for reasons previously discussed. However, since the unit as a whole is topographically continuous with and shares geomorphic features with Asp4, it is probable that the underlying bedrock is part of the Asp4 unit.

Therefore, based on present topographic variation, interpreted stratigraphic relationships, and crater retention model ages, the interpretive minimum sequence of events is (Fig. 19):

1. >1 Ga: Formation and modification of the Noachian cratered highlands. A topographic low is produced by an unknown mechanism (possibly initial flooding events), providing accommodation space for later basin fill.
2. 700–1000 Ma: Deposition of Asp1 flows, stratigraphically continuous with AHv of the Tharsis Montes Formation to the east.
3. 700–800 Ma: Initial, or continued, carving of Mangala Valles into Noachian Highlands bedrock and formation of both the central and western of the northwestern channels by aqueous outburst sourced at Mangala Fossa.
4. 400–500 Ma: A series of flood lava flow events sourced from Mangala Fossa, which extended along the majority of the southern and central valley toward the northern and northwestern reaches of the system, partially filling the easternmost northern channel and filling the central northwestern channel nearly to its mouth.

5. ~400 Ma: Another aqueous megaflooding event, which deepened and resurfaced the western side of the valley, widened the original northwestern channels and incised the youngest, easternmost northwestern channel, segmented the entire western margin of the Asp2 volcanic assemblage, and carved canyons into and partially resurfaced its interior.
6. 300–400 Ma: Continuation of effusive volcanism in relatively low volumes, resulting in the emplacement of the youngest flow along the new topographic lows to form Asp3 surfaces.
7. ~300 Ma: Emplacement of eolian sedimentary deposits of unknown source in the northern portion of the study area.

The above dates are given based on crater counts of presently exposed surfaces. Older surfaces that have been modified or buried by later flows and channels cannot be dated, therefore it is difficult to place a reliable lower time constraint on phases of volcanism and channel formation. The events listed above only include those that are directly supported by our observations. We cannot rule out possible additional events that were erased by the events that followed, especially those that preceded the oldest flooding event resolved in our crater counts. Therefore, it is entirely possible that Mangala Valles was primarily incised during multiple megaflooding events that took place within the timeframe of 1–3 Ga.

4.5. Comparison with previous work

Our geological maps, unit interpretations, and conclusions generally agree with those of Tanaka and Chapman (1990) and Chapman and Tanaka (1993). These authors hypothesized that there was an initial chaotic fluvial outburst event that carved the original valley, followed by a phase of volcanism that deposited large volcanic plateaus, possibly in concert with more fluvial activity. We generally agree with this hypothesis and augment these interpretations by constraining the sequence of events to include at least seven distinct events or phases. Studies favoring dominantly fluvial processes within Mangala Valles (Zimbelman et al., 1992; Ghatan et al., 2005; Basilevsky et al., 2008) differ from our interpretations in some crucial ways. For instance, volcanic processes, apparent in higher-resolution image data, may better explain some of the features in these studies that were interpreted as produced by fluvial processes. On the other hand, many of the features we have identified are difficult to explain by volcanic processes alone. We also note that while we cannot rule out the potential role of glacial processes in the formation of the geomorphology of Mangala Valles, we see no features that support that interpretation. Overall, we find that volcanic, fluvial, or eolian processes can explain each geomorphology observed, either alone or in combination.

5. Conclusions

Results from our mapping and crater counts suggest the occurrence of at least three major volcanic phases and at least two major fluvial events. Given our observations, Mangala Valles was carved by at least one large fluvial event—likely chaotic outburst flooding event(s) resulting from dike intrusion of the subsurface hydrological system at Mangala Fossa—one of which occurred ~700–800 Ma. This event occurred within the timeframe of

the deposition of pahoehoe-like lavas from Tharsis at the northeastern portion of the system during ~700–1000 Ma. A second volcanic phase ending at ~400 Ma saw the emplacement of multiple voluminous, fluid lava flows sourced at Mangala Fossa that filled the majority of the valley. At ~350–400 Ma, another megaflooding event of similar scale to the first resurfaced and expanded the valley. A final volcanic phase occurring at ~350 Ma filled the west valley and much of the floors of the northwestern channels. Although the duration of each phase remains uncertain, it is clear that Mangala Valles remained active over a considerable period of time, with a recurrence of volcanic episodes in between major fluvial episodes.

The close interplay of fluvial and volcanic activity suggests that fluvial activity not only played a major role during a period of volcanism, but also may be linked to, or even triggered by, volcanic processes. If the cryospheric seal of a subsurface aquifer is subject to heating by intrusive igneous activity, resulting in fracture and catastrophic release of its hydrologic reservoir (as modeled by Wilson and Head (2002) and Thakur et al. (2007)), then subsequent eruptive activity may logically follow. Evidence of repeated episodic behavior therefore indicates recharging and repeated interaction of hydrological and igneous subsurface sources over a relatively long period of time in the Late Amazonian. Such activity was no doubt bolstered by the structural activity in the area, the relative youth of which is apparent in the cross-cutting relationships between thrust faults and the younger units (e.g., Fig. 16B) (see Tanaka and Chapman (1990) for detailed discussion of regional structural relations). This intimate relationship between tectonic, volcanic, and aqueous activity augments current ideas about complexity of the Memnonia Fossae region and its relationship to Tharsis-related volcanism and tectonics. Ares Valles and the Kasei Valles and Echus Chasma system have been suggested to share this episodic behavior, but at a much earlier time in martian history (Warner et al., 2009; Chapman et al., 2010), indicating that Mangala Valles represents a younger expression of what may be a similar subsurface process. Detailed comparative studies of other more recently active fluvial–volcanic systems, such as Athabasca Valles (Jaeger et al., 2007, 2010), may aid in determining the extent to which repeated fluvial and volcanic activity has extended into the Amazonian Period. Comparing the timing and global distribution of these events may also provide insight into whether or not this activity has occurred within isolated systems, or has instead been associated with high-volume, planetary-scale volcanic pulses (Anderson et al., 2001; Wilson et al., 2001; Neukum et al., 2010).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We are grateful for the detailed and insightful reviews provided by Jim Zimbelman and Mary Chapman. The MRO project and Arizona State University School of Earth and Space Exploration supported this work. CWH acknowledges funding support from MDAP Grant # NNX13AK62G.

References

- Anderson RC, et al. Primary centers and secondary concentrations of tectonic activity through time in the western hemisphere of Mars. *J Geophys Res.* 2001; 106(E9):20563–20586.
- Baker, VR. Erosional forms and processes for the catastrophic Pleistocene Missoula floods in eastern Washington. In: Morisawa, M., editor. *Fluvial Geomorphology*. State Univ. of New York; Binghamton, NY: 1973. p. 123–148.
- Baker VR, Kochel RC. Martian channel morphology: Maja and Kasei Valles. *J Geophys Res – Solid Earth.* 1979; 84(B14):7961–7983.
- Baker VR, Milton D. Erosion by catastrophic floods on Mars and Earth. *Icarus.* 1974; 23:27–41.
- Baker VR, Komatsu G, Parker TJ, Gulick VC, Kargel JS, Lewis JS. Channels and valleys on Venus: Preliminary analysis of Magellan data. *J Geophys Res.* 1992; 97(E8):13421–13444.
- Bargery AS, Wilson L. Erosive flood events on the surface of Mars: Application to Mangala and Athabasca Valles. *Icarus.* 2011; 212(2):520–540.
- Basilevsky AT, et al. Episodes of floods in Mangala Valles, Mars, from the analysis of HRSC, MOC and THEMIS images. *Planet Space Sci.* 2008; 57:917–943.
- Burr, DM., Baker, VR., Carling, PA. *Megaflooding on Earth and Mars*. Cambridge Univ. Press; Cambridge: 2009. p. 311
- Byrne PK, et al. An assemblage of lava flow features on Mercury. *J Geophys Res – Planets.* 2013; 118(6):1303–1322.
- Carr MH, Head JW. Geologic history of Mars. *Earth Planet Sci Lett.* 2010; 294(3):185–203.
- Carr MH, Baum WA, Briggs GA, Masursky H, Wise DW, Montgomery DR. Imaging experiment: The Viking Mars orbiter. *Icarus.* 1972; 16:17–33.
- Chapman MG, Tanaka KL. Small valleys and hydrologic history of the lower Mangala Valles region, Mars. *Proc Lunar Sci Conf.* 1990; 20:531–539.
- Chapman, MG., Tanaka, KL. US Geol Surv Misc Invest Map I-2294. Reston, VA: 1993. Geologic Map of the MTM –05152 and –10152 Quadrangles, Mangala Valles Region of Mars.
- Chapman, MG., Masursky, H., Dial, AL, Jr. US Geol Surv Misc Invest Map I-1696. Reston, VA: 1989a. Geologic Map of Science Study Area 1A, East Mangala Valles Region of Mars.
- Chapman, MG., Masursky, H., Dial, AL, Jr. US Geol Surv Misc Invest Map I-1697. Reston, VA: 1989b. Geologic Map of Science Study Area 1A, East Mangala Valles Region of Mars.
- Chapman, MG., Masursky, H., Dial, AL, Jr. US Geol Surv Misc Invest Map I-1962. Reston, VA: 1989c. Geologic Map of Science Study Area 1A, East Mangala Valles Region of Mars.
- Chapman, MG., Masursky, H., Dial, AL, Jr. US Geol Surv Misc Invest Map I-2087. Reston, VA: 1991. Geologic Map of Science Study Area 1B, West Mangala Valles Region of Mars.
- Chapman MG, Gudmundsson MT, Russell AJ, Hare TM. Possible Juventae Chasma subice volcanic eruptions and Maja Valles ice outburst floods on Mars: Implications of Mars Global Surveyor crater densities, geomorphology, and topography. *J Geophys Res.* 2003; 108(E10):5113.
- Chapman MG, et al. Noachian–Hesperian geologic history of the Echus Chasma and Kasei Valles system on Mars: New data and interpretations. *Earth Planet Sci Lett.* 2010; 294(3–4):256–271.
- Christensen PR, Jakosky B, Kieffer H. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. *Space Sci Rev.* 2004; 110:85–130.
- Craddock, RA., Greeley, R. US Geol Surv Misc Invest Map I-2310. Reston, VA: 1994. Geologic Map of the MTM –20147 Quadrangle, Mangala Valles Region of Mars.
- Cutts JA, Blasius KR. Origin of martian outflow channels: The eolian hypothesis. *J Geophys Res – Solid Earth.* 1981; 86(B6):5075–5102.
- Edwards CS, Nowicki KJ, Christensen PR, Hill J, Gorelick N, Murray K. Mosaicking of global planetary image datasets: 1. Techniques and data processing for Thermal Emission Imaging System (THEMIS) multi-spectral data. *J Geophys Res.* 2011; 116:E10008.
- Ghatan GJ, Head JW, Wilson L. Mangala Valles, Mars: Assessment of early stages of flooding and downstream flood evolution. *Earth Moon Planets.* 2005; 96:1–57.
- Greeley R, Theilig E, Guest JE, Carr MH, Masursky H, Cutts JA. Geology of Chryse Planitia. *J Geophys Res.* 1977; 82(28):4093–4109.

- Hartmann WK. Martian cratering 8: Isochron refinement and the chronology of Mars. *Icarus*. 2005; 174(2):294–320.
- Head JW. Lunar volcanism in space and time. *Rev Geophys*. 1976; 14(2):265–300.
- Head JW, Marchant DR, Ghatan GJ. Glacial deposits on the rim of a Hesperian–Amazonian outflow channel source trough: Mangala Valles, Mars. *J Geophys Res*. 2004; 31(10):L10701.
- Hill, J., Edwards, CS., Christensen, PR. Mapping the martian surface with THEMIS infrared global mosaics. 8th Int. Conf. Mars; 2014. Abstract 1141
- Jaeger WL, Keszthelyi LP, McEwen AS. Athabasca Valles, Mars: A lava-draped channel system. *Science*. 2007; 317:1709–1711. [PubMed: 17885126]
- Jaeger WL, Keszthelyi LP, Skinner JA Jr, Milazzo MP, McEwen AS, Titus TN, Rosiek MR, Galuszka DM, Howington-Kraus E, Kirk RL. Emplacement of the youngest flood lava on Mars: A short, turbulent story. *Icarus*. 2010; 205:230–243.
- Jaumann R, Neukum G, Behnke T, Duxbury T. HRSC Co-Investigator Team. The High-Resolution Stereo Camera (HRSC) experiment on Mars Express: Instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. *Planet Space Sci*. 2007; 55(7–8):928–952.
- Keszthelyi LP, McEwen AS, Thordarson T. Terrestrial analogs and thermal models for martian flood lavas. *J Geophys Res*. 2000; 105(E6):15027–15049.
- Keszthelyi LP, Thordarson T, McEwen AS, Haack H, Guilbaud M, Self S, Rossi MJ. Icelandic analogs to martian flood lavas. *Geochem Geophys Geosyst*. 2004; 5(11):1–32.
- Komar P. Comparisons of the hydraulics of water flows in martian outflow channels with flows of similar scale on Earth. *Icarus*. 1979; 37(1):156–181.
- Lamb MP, Dietrich WE, Aciego SM, DePaolo DJ, Manga M. Formation of Box Canyon, Idaho, by megaflood: Implications for seepage erosion on Earth and Mars. *Science*. 2008; 320:1067–1070. [PubMed: 18497296]
- Leverington DW. Volcanic rilles, streamlined islands, and the origin of outflow channels on Mars. *J Geophys Res – Planets*. 2004; 109:E10011.
- Leverington DW. Was the Mangala Valles system incised by volcanic flows? *J Geophys Res*. 2007; 112:E11005.
- Levy JS, Head JW. Evidence for remnants of ancient ice-rich deposits: Mangala Valles outflow channel, Mars. *Terra Nova*. 2005; 17(6):503–509.
- Lucchitta BK. Ice sculpture in the martian outflow channels. *J Geophys Res*. 1982; 87(B12):9951–9973.
- Malin MC, Edgett KS. Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. *J Geophys Res – Planets*. 2001; 106(E10):23429–23570.
- Malin MC, Bell J, Cantor B, Caplinger M. Context Camera investigation on board the Mars Reconnaissance Orbiter. *J Geophys Res*. 2007; 112(E5)
- Mars Channel Working Group. Channels and valleys on Mars. *Geol Soc Am Bull*. 1983; 94:1035–1054.
- McCauley JF, Carr MH, Cutts JA, Hartmann WK, Masursky H, Milton DJ, Sharp RP, Wilhelms DE. Preliminary Mariner 9 report on the geology of Mars. *Icarus*. 1972; 17:289–327.
- McEwen AS, Eliason E, Bergstrom J. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *J Geophys Res*. 2007; 112(E5)
- McEwen AS, Keszthelyi LP, Grant JA. Have there been large, recent water floods on Mars? *Lunar Planet Sci*. 2012:43. Abstract 1612.
- Michael GG. Planetary surface dating from crater size-frequency distribution measurements: Multiple resurfacing episodes and differential isochron fitting. *Icarus*. 2013; 226:885–890.
- Michael GG, Neukum G. Planetary surface dating from crater size-frequency distribution measurements: Partial resurfacing events and statistical age uncertainty. *Earth Planet Sci Lett*. 2010; 294:223–229.
- Milton, DJ. US Geol Surv Misc Invest Map I-894. Reston, VA: 1974. Geologic Map of the Lunae Palus Quadrangle of Mars.

- Neukum G, et al. The geologic evolution of Mars: Episodicity of resurfacing events and ages from cratering analysis of image data and correlation with radiometric ages of martian meteorites. *Earth Planet Sci Lett.* 2010; 294:204–222.
- Nummedal D, Prior DB. Generation of martian chaos and channels by debris flows. *Icarus.* 1981; 45(1):77–86.
- Sharp RP, Malin MC. Channels on Mars. *Geol Soc Am Bull.* 1975; 86(5):593–609.
- Skinner JA Jr, Hare TM, Tanaka KL. Digital renovation of the Atlas of Mars 1:15,000,000-scale global geologic series maps. *Lunar Planet Sci.* 2006:37. Abstract 2331.
- Smith DE, Zuber M, Frey H, Garvin J. Mars Orbiter Laser Altimeter: Experiment summary after the first year of global mapping of Mars. *J Geophys Res.* 2001; 106(E10):23689–23722.
- Tanaka KL, Chapman MG. The relation of catastrophic flooding of Mangala Valles, Mars, to faulting of Memnonia Fossae and Tharsis volcanism. *J Geophys Res.* 1990; 95(B9):14315–14323.
- Tanaka KL, et al. Geologic Map of Mars. US Geol Surv Sci Invest Map I-3292. 2014
- Thakur PK, Bhardwaj A, Aggarwal SP. Hydrological Parameter Extraction and Analysis of Mangala Valles of Mars. *LPI Contrib.* 2007; 1353:3116.
- Walker GPL. Structure, and origin by injection of lava under surface crust, of tumuli, ‘lava rises’, ‘lava-rise pits’, and ‘lava-inflation clefts’. *Bull Volcanol.* 1991; 53(7):546–558.
- Warner N, Gupta S, Muller J, Kim J, Lin S. A refined chronology of catastrophic outflow events in Ares Vallis, Mars. *Earth Planet Sci Lett.* 2009; 288(1–2):58–69.
- Wilson L, Head JW. Tharsis-radial graben systems as the surface manifestation of plume-related dike intrusion complexes: Models and implications. *J Geophys Res.* 2002; 107(E8)
- Wilson L, Scott ED, Head JW. Evidence for episodicity in the magma supply to the large Tharsis volcanoes. *J Geophys Res.* 2001; 106(E1):1423–1434.
- Wilson L, Mouginis-Mark PJ, Tyson S, Mackown J, Garbeil H. Fissure eruptions in Tharsis, Mars: Implications for eruption conditions and magma sources. *J Volcanol Geotherm Res.* 2009; 185:28–46.
- Zimbelman JR, Craddock RA, Greeley R, Kuzmin RO. Volatile history of Mangala Valles, Mars. *J Geophys Res.* 1992; 97(E11)
- Zimbelman, JR., Craddock, RA., Greeley, R. US Geol Surv Misc Invest Map I-2402. Reston, VA: 1994. Geologic Map of the MTM-15147 Quadrangle, Mangala Valles Region of Mars.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.icarus.2014.09.040>.

Fig. 1. Regional context map showing MOLA shaded relief mosaic map overlain by a simplified geologic map based on the global map from Skinner et al. (2006). Black inset denotes the study area. All maps use cylindrical projection.

Fig. 2.
MOLA shaded relief/colorized elevation map of study area with white insets denoting figure reference locations. Contour interval 100 m. For the color version of this figure, the reader is referred to the web version of this article.

Fig. 3.
A complete geomorphic map of the study area with a THEMIS Day IR v11.6 mosaic base.

Fig. 4.
A detailed view of the southern portion of the map (THEMIS Day IR v11.6 mosaic base).

Fig. 5.

A detailed view of the mapped northwestern channels (THEMIS Day IR v11.6 mosaic base).

Fig. 6. Typical rough terrain (Hrt) surfaces. (A) CTX B19_017111_1738_XN_06S154W and (B) CTX B02_010531_1704_XI_09S153W. Illumination is from the left and north is up in all images.

Fig. 7.

(A) Hrt embayed by Asp1 on the right (CTX P15_006760_1658_XN_14S148W). (B) An impact crater within Asp1 whose wall has been breached and floor filled (CTX G22_026829_1658_XN_14S147W). (C) Sinuous channel feature in Asp1 (CTX G22_026829_1658_XN_14S147W).

Fig. 8.
 (A) Typical Ast appearance with ridges and a channel terrace (indicated by white arrows) (CTX P19_008474_1688_XN_11S150W). (B) Diverging linear ridges in Ast (CTX P05_002857_1629_XN_17S149W). (C) Hrt landscape dissected by Ast ridges (CTX B02_010531_1704_XI_09S153W).

Fig. 9.
Streamlined islands of the Alk unit within Ast. Note the flat tops of these knobs. (A) CTX
P14_006615_1645_XN_15S149W and (B) CTX B02_010531_1704_XI_09S153W.

Fig. 10.

(A) Uniform appearance of Asp2 and its lobate edges (CTX D01_027462_1658_XN_14S148W). (B) Inverted Asp2 channel in northwestern Mangala channels (CTX P01_001525_1700_XN_10S151W). (C) Grooved slope (Ags) features along the margin of Asp2. Note that Ags flow features tend to begin oriented perpendicular to the plateau edge (CTX P03_002079_1639_XN_16S149W). (D) An embayed crater and bar in Asp2 (CTX P15_006760_1658_XN_14S148W). (E) Wide trough in Asp2 (CTX P03_002079_1639_XN_16S149W).

Fig. 11.
A large impact crater circumvented by a wide canyon (CTX
B01_010188_1655_XI_14S148W).

Fig. 12.

(A) Polygons of the Apb unit (CTX P16_007182_1626_XN_17S150W). (B) Embayed knobs of the Ask unit (CTX P05_002857_1629_XN_17S149W). (C) Terraced scoured (Ats) unit (CTX P16_007182_1626_XN_17S150W). (D) Blocky margin of Asp2, most likely a transitional phase from Asp2 to Apb (CTX P03_002079_1639_XN_16S149W).

Fig. 13.

(A) Sinuous channels in Asp3 along a contact with Ast (right) (CTX P01_001393_1655_XN_14S149W). (B) Meandering channels in Asp3 at the valley mouth (CTX P05_002857_1629_XN_17S149W). (C) Unusual pits found in Asp3 (CTX P19_008474_1688_XN_11S150W). (D) A location where Asp3 has draped Ast, resulting in muted ridged topography (CTX P01_001591_1708_XN_09S151W). (E) A lobate flow front in Asp3 truncating Ast ridges (CTX P05_002857_1629_XN_17S149W).

Fig. 14.

(A) Large partially buried crater in Asp4. Note muted appearance of small crater rims (CTX B09_013234_1704_XN_09S149W). (B) Asp4 landscape with muted streamlined landforms (CTX B09_013234_1704_XN_09S149W).

Fig. 15. Bar plot showing model ages from crater counts arranged in order of decreasing average age with standard errors shown in red. The background colors correspond to the geomorphic map unit colors in Fig. 3. For the color version of this figure, the reader is referred to the web version of this article.

Fig. 16.

(A) Amphitheater-headed canyon at the end of an Ast channel (CTX P22_009476_1756_XN_04S150W). (B) Grooved slope (Ags) off of a local Asp2 plateau margin, grading into Ast to the northwest. White arrows indicate interpreted flow direction. A fault can be seen beginning from the bottom right and cutting through Asp2 bedrock toward the northwest (CTX P08_003991_1636_XN_16S148W). (C) Amphitheater-headed canyons cutting into the margin of Asp2 (CTX B01_010188_1655_XI_14S148W).

Fig. 17.
(A) Ridged flow front in Asp3 (CTX G22_026816_1706_XN_09S153W). (B) Lavas tube collapse pits in Asp3 (CTX P13_006114_1748_XN_05S151W).

Fig. 18. Interpretive geologic map showing hypothesized current extent of bedrock units and the distribution of fluvial modification and substantial eolian deposition (THEMIS Day IR v11.6 mosaic base).

Fig. 19.

Inferred minimum sequence of events as interpreted from crater counts and stratigraphic relations. (a) >1 Ga: A topographic low is produced by an unknown mechanism to an unknown extent, providing accommodation space for later basin fill. (b) 700–1000 Ma: Deposition of Tharsis lava flows (brown) from the east. The southern extent of these flows is unknown. (c) 700–800 Ma: Flooding and incision of Mangala Valles into highland bedrock, sourced at Mangala Fossa. Extent of incision crosshatched, arrows indicate flow direction. Note that there is no evidence suggesting that this was the first flooding/incising event to occur in Mangala. It is entirely possible that older events took place whose evidence has been erased by subsequent events. (d) 400–500 Ma: Deposition of relatively young voluminous lava flows into the valles, sourced at Mangala Fossa (orange). (e) ~ 400 Ma: Another valley-carving flooding event that deepened and widened the valles toward the west and incised a third northwestern channel. (f) 300–400 Ma: Emplacement of youngest volcanic units along the new topographic low to the west (yellow) and emplacement of sedimentary deposits in the north (extent dotted). The colors in this figure correspond with those used in Fig. 18. For the color version of this figure, the reader is referred to the web version of this article.

Table 1

Summary table of the results of 30 crater counts performed within the study area. Errors presented are the standard error of fit. See Supplementary materials for map of area locations and individual size frequency distribution plots.

Sample area	Unit	Example figure(s)	Area (km ²)	Crater retention age (Ma)	N	Minimum diameter bin (m)	Maximum diameter bin (m)
1	Asp4	14	300	243 ± 18	328	62.5	354
2	Asp4	14	300	302 ± 46	59	125	250
3	Asp4	14	500	419 ± 50	118	125	354
4	Asp4	14	300	357 ± 29	200	88.4	250
5	Asp3	13	90	316 ± 33	147	62.5	250
6	Asp3	13	200	375 ± 26	344	62.5	354
7	Asp3	13	100	348 ± 65	53	88.4	354
8	Ags	10c, 10e, 11, 19	200	372 ± 61	55	125	354
9	Ags	10c, 10e, 11, 19	100	410 ± 44	141	62.5	250
10	Asp2	10a, 10d	100	387 ± 41	127	62.5	354
11	Asp2	10a, 10d	500	452 ± 27	374	88.4	250
12	Asp2	10a, 10d	100	448 ± 44	168	62.5	500
13	Asp2	10a, 10d	70	491 ± 45	159	62.5	177
14	Asp2	10a, 10d	400	393 ± 28	266	88.4	354
15	Ast	8	100	739 ± 71	153	88.4	500
16	Ast	8	200	746 ± 52	313	88.4	250
17	Ast	8	200	770 ± 54	317	88.4	250
18	Ast	8	100	828 ± 54	398	62.5	354
19	Ast	8	100	794 ± 87	143	88.4	354
20	Asp1	7	100	719 ± 70	161	88.4	500
21	Asp1	7	200	961 ± 75	289	88.4	250
22	Asp1	7	300	955 ± 51	552	88.4	500
23	Hrt	6	200	3590 ± 20	264	177	707
24	Hrt	6	100	3770 ± 30	68	250	1000
25	AHv	n/a	600	363 ± 25	374	88.4	707
26	AHv	n/a	300	386 ± 21	553	62.5	354
27	AHv	n/a	200	1160 ± 130	123	125	500

Sample area	Unit	Example figure(s)	Area (km ²)	Crater retention age (Ma)	N	Minimum diameter bin (m)	Maximum diameter bin (m)
28	AHv	n/a	200	1370 ± 80	201	125	500
29	IHt	n/a	200	635 ± 87	96	125	500
30	eHv	n/a	200	517 ± 45	201	88.4	250

Table 2

Summary table of interpretations of discussed geomorphologies. Note that evidence of eolian activity is present on all surfaces, and is therefore not listed unless extensive.

Unit	Bedrock	Modification	Interpretation
Hrt	Nh	Fluvial overland flow erosion, eolian erosion	Fluvial and eolian resurfacing of high-standing bedrock
Asp1	AHv	None	Flood basalt. Fill from AHv to the east
Ast	Nh	Fluvial erosion	Fluvial erosion of Nh
Alk	Asp2/Nh	Fluvial erosion	Streamlined islands
Asp2	Asp2	Fluvial overland flow erosion	Volcanic plateau with post-emplacement flooding
Ags	Asp2	Fluvial erosion	Fluvial erosion of Asp2
Apb	Asp2	Fluvial erosion	Fluvial erosion of Asp2
Ask	Asp2	Fluvial erosion	Fluvial erosion of Asp2
Ats	Asp2	Fluvial erosion	Fluvial channel terraces
Asp3	Asp3	None	Young lava flow
Asp4	Asp2	Eolian deposition	Tephra/dust cover overlying lava flow(s)