GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48971.1

Manuscript received 19 February 2021
Revised manuscript received 27 April 2021
Manuscript accepted 10 May 2021

Published online 24 June 2021

A record of syn-tectonic sedimentation revealed by perched alluvial fan deposits in Valles Marineris, Mars

J.M. Davis[1]*, P.M. Grindrod[1], S.G. Banham[2], N.H. Warner[3], S.J. Conway[4], S.J. Boazman[1] and S. Gupta[2]
[1]Department of Earth Sciences, Natural History Museum, London SW7 5BD, UK
[2]Department of Earth Science and Engineering, Imperial College, London SW7 2BP, UK
[3]Department of Geological Sciences, State University of New York at Geneseo, Geneseo, New York 14454, USA
[4]Laboratoire de Planétologie et Géodynamique, CNRS, UMR 6112, Université de Nantes, 44322 Nantes, France

ABSTRACT

On Mars, basins formed by tectonic processes are rare and mostly have unconstrained subsidence histories. One method for understanding this record of subsidence is through associated alluvial fans, which are sourced from uplifted areas and accumulate in downthrown basins. The source, morphology, and superposition of fan deposits can be used to reconstruct fault kinematics, the relative timing of accommodation space formation, and, in turn, the influence tectonic processes had on Martian fan formation. Here we use high-resolution orbital data sets to characterize sediment fan deposits associated with syn-tectonic sedimentation in two regions of the Valles Marineris canyons: Coprates Chasma and Juventae Chasma. These deposits comprise sediment fans on the current canyon floor and low-gradient surfaces perched several kilometers above the canyon floor. We interpret the low-gradient surfaces as remnant sediment fan deposits, which originally formed at the former canyon floor and have since been offset due to normal faulting. The preservation of vertically offset generations of sediment fan deposits supports a progressive, basinward migration of fault activity into the original hanging wall or repeat activity along a fault zone. Each episode of faulting was followed by a basinward shift in drainages, which led to fault-scarp degradation and formation of a new generation of fans. Multiple episodes of syn-tectonic sedimentation occurred during the evolution of the basins, with fluvial activity sporadically active. Our results demonstrate, for the first time on Mars, that depositional cyclicity was linked to tectonic deformation, possibly representative of regional processes throughout Valles Marineris.

INTRODUCTION

Alluvial fans are abundant on Mars, and most are considered to postdate the period of global fluvial activity at the Noachian-Hesperian boundary (3.7 Ga; Fassett and Head, 2008), instead forming later during the drier Hesperian and Amazonian eras (<3.7 Ga; Grant and Wilson, 2011; Morgan et al., 2014). Recent work has suggested that these alluvial fans formed during infrequent wet episodes in an otherwise dry climate (Kite et al., 2017, 2019). Unlike on Earth, most Martian alluvial fans occur at impact-crater margins (Moore and Howard, 2005; Palucis et al., 2014; Wilson et al., 2021) and are not linked to tectonically active basins. The absence of Earth-like tectonics on Mars, which would have generated fault-bounded basins, may have inhibited conditions suitable for more widespread alluvial fan development outside impact craters, where relative uplift creates an area of provenance adjacent to a downthrown basin suitable for continuous sediment accumulation (Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000).

The Valles Marineris equatorial canyons are one of the largest sediment sinks on Mars and contain an extensive array of aqueously altered sedimentary deposits (Weitz et al., 2008; Warner et al., 2013; Davis et al., 2018). Alluvial fans in Valles Marineris, which may have been deposited into active tectonic basins, provide an ideal location for exploring the role of tectonic processes on Martian fan formation and the relative timing of syn-depositional fault activity. We document the impact of faulting on alluvial fan systems at two sites in Valles Marineris, southeastern Coprates Chasma and Juventae Chasma, focusing on the relative timing of sedimentation and normal faulting. We use images from the High Resolution Imaging Science Experiment (HiRISE; 0.25 m/px; McEwen et al., 2007) and Context Camera (CTX; 6 m/px; Malin et al., 2007) instruments aboard Mars Reconnaissance Orbiter (MRO) and CTX topographic (20 m/px) data sets to map fan morphology and analyze the relation of the fans to basin development. We identify multiple distinct periods of sedimentation, manifested as discrete sediment fans at different elevations and stratigraphic position in the canyon, with implications for understanding the interplay between tectonic and sedimentary processes.

GEOLOGIC SETTING OF VALLES MARINERIS

Valles Marineris is a 4000-km-long, west-east–trending system of canyons found east of the Tharsis volcanic bulge. Despite superficial similarities to extensional rift basins on Earth, the formation of Valles Marineris was likely driven by a combination of subsidence along near-vertical normal faults, modest extension radial to the nearby Tharsis volcanoes, and sedimentation (Anderson et al., 2001; Andrews-Hanna, 2012a, 2012b). Valles Marineris likely opened eastward from the late Noachian to Amazonian (Anderson et al., 2001). Our main study site, southeastern Coprates Chasma, is situated in eastern Valles Marineris along its south wall (Fig. 1; Fig. S1 in the Supplemental Material[1]). Our study area in Coprates Chasma is 60 km

*E-mail: joel.davis@nhm.ac.uk

[1]Supplemental Material. Figures S1–S8, Table S1 (fan characteristics), and Table S2 (instrument and image ID numbers). Please visit https://doi.org/10.1130/GEOL.S.14781930 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Davis, J.M., et al., 2021, A record of syn-tectonic sedimentation revealed by perched alluvial fan deposits in Valles Marineris, Mars: Geology, v. 49, p. 1250–1254, https://doi.org/10.1130/G48971.1

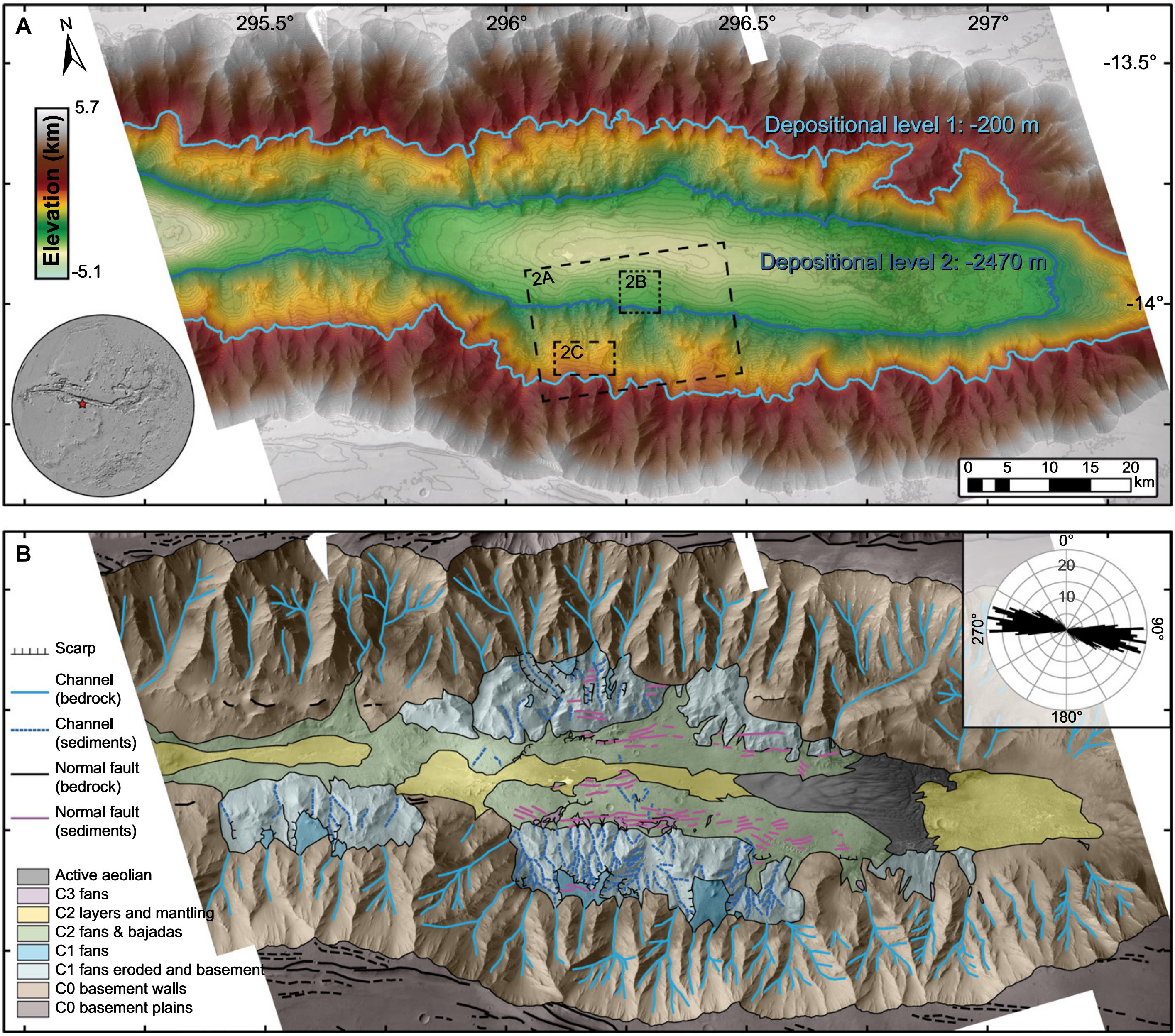

Figure 1. (A) Stereo Context Camera (CTX) topographic map of the southeastern Coprates Chasma (Mars) study site, showing vertically separated levels of sediment deposition. Rectangles indicate location of Figure 2 panels. (B) Geologic map of the study site, showing alluvial fans, bajadas, their catchment, and faults. Rose diagram shows normal-fault orientations.

wide by 90 km long and 8 km deep with 30°–40° wall slopes (Fig. 1). We also investigate Juventae Chasma, which is detached from the main Valles Marineris canyons (Fig. S1). Our study area in Juventae Chasma comprises a 30-km-wide by 70-km-long, 6-km-deep section along its south wall, away from the northern region of Juventae where trough development has been influenced by the formation of the outflow channel, Maja Vallis (Sarkar et al., 2019).

SEDIMENT FANS ON THE SOUTHEASTERN COPRATES CHASMA CANYON FLOOR

The current canyon floor of southeastern Coprates Chasma is covered by a prominent set of kilometer-scale sediment fans that emerge from drainage gullies incised into the canyon walls (Figs. 1 and 2A; Fig. S2). Fan apices cluster at −2470 ± 190 m elevation. These fans merge laterally to form extensive bajadas along the canyon length on both sides of the canyon (Fig. 1B; Fig. S2). The catchments feeding the fans extend to the canyon plateau edge (Fig. S3). The surface slopes of the sediment fans range between 5° and 12° (Table S1). Multiple distributary channels (30–100 m wide) radiate from the fan apices, in some cases extending to the distal margins of the fans (Fig. 2B; Fig. S2A). Linear ridges (20–60 m wide, <5 km long) are distributed in similar patterns across fan surfaces (Figs. S2B and S2C) and are observed to commonly superpose one another. We interpret these as inverted fluvial channel deposits (e.g., Davis et al., 2016). On other fan surfaces, paired ridges (5–10 m high; Fig. 2B) occur at the lateral margins of channels. At the distal margins of the fans, we observe meter- to decameter-scale light- and mid-toned layered deposits (Fig. 2A; Fig. S2D) that contain hydrous minerals (e.g., Fe-Mg phyllosilicates) in Compact Reconnaissance Imaging Spectrometer for Mars data (MRO; Murchie et al., 2007; Fig. S4). Embedded within the fans are impact craters as large as 400 m in diameter (Fig. S2E).

The morphology and topographic setting of the sediment fans are consistent with subaerial alluvial fans (Blair and McPherson, 1994).

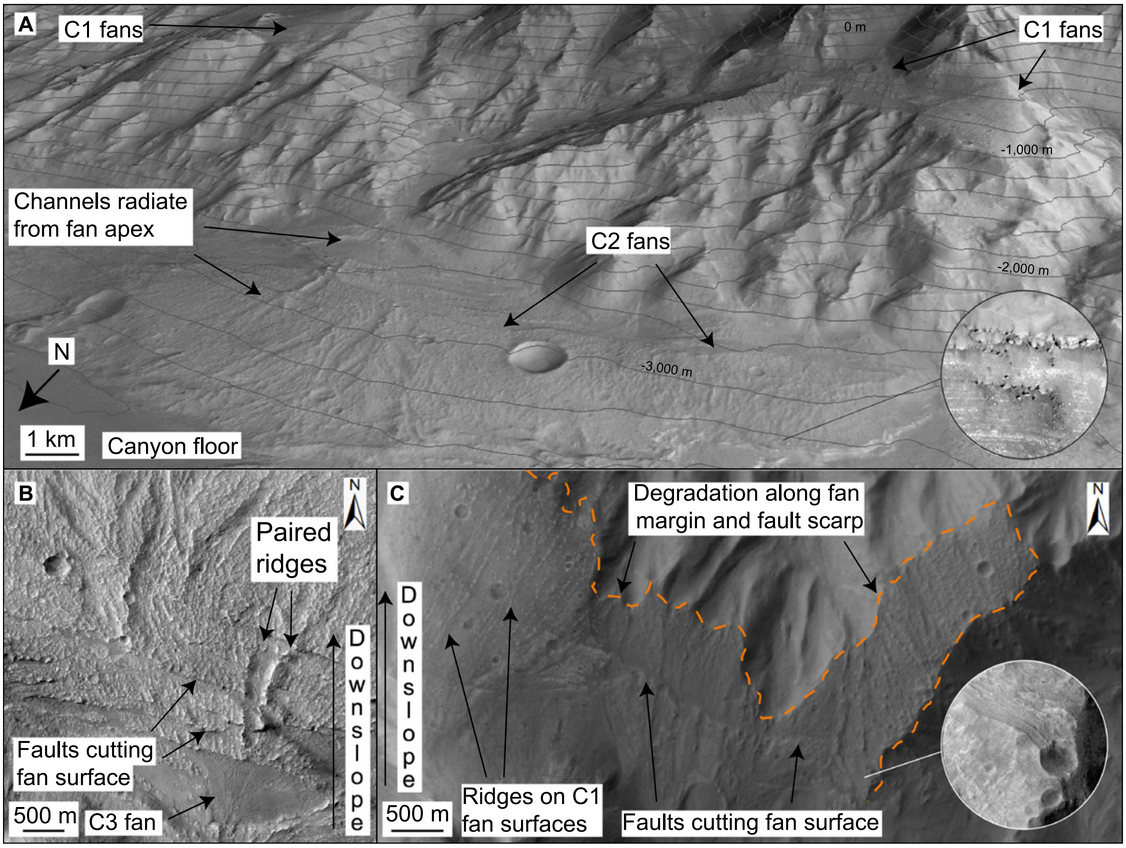

Figure 2. Faulted alluvial fan deposits in southeastern Coprates Chasma, Mars. (A) Oblique Context Camera (CTX) image of multiple generations of alluvial fan deposits, offset by faulting. Inset shows High Resolution Imaging Science Experiment (HiRISE) image of bright-toned layering in fan margins. Topographic contour interval is 200 m. (B) HiRISE mosaic of C2 alluvial fan deposits on canyon floor, where surfaces contain distributary channels and paired ridges, cut by multiple faults. Youngest C3 fans superpose faults and are local to C2 fan apices. (C) Planform CTX mosaic of oldest (C1) alluvial fan deposits (perched terraces), which have been faulted and later eroded (orange line). Inset shows layering exposed in fan margins.

The presence of inverted distributary channels is evidence for both streamflow and debris-flow processes. The fan surface slopes are comparable to those of debris-flow fans or of debris-flow fans later modified by fluvial processes (6°–17°; Williams et al., 2006). Short, steep catchments and paired lateral ridges are also associated with debris-flow fans (Blair and McPherson, 1994; Harvey, 1997). Impact craters embedded in the fans indicate that the alluvial fans formed over multiple intermittent flow events (Kite et al., 2017). The hydrous mineral–bearing layered deposits in fan margins are similar to those suggestive of a lacustrine or playa setting in the adjacent southeastern Coprates Catena canyon (Grindrod et al., 2012, 2018). In summary, the sedimentary deposits on the southeastern Coprates Chasma canyon floor are consistent with intermittently formed alluvial fans, with evidence for a hybrid of debris-flow and fluvial processes and for playas or lacustrine environments at their distal margins.

EVIDENCE FOR FAULTING AND FURTHER SEDIMENTATION ON THE CANYON FLOOR

Linear, west-east–trending topographic offsets (10–50 m vertical offset) are visible within the canyon floor fans, which are consistently parallel to the canyon wall (Figs. 1B and 2B; Fig. S2). We interpret these features as normal faults that have downthrown the canyon-floor fan deposits basinward (herein referred to as the second generation of Coprates fans, C2). On the south wall, these faults are embayed by younger fans (C3 fans), albeit on a smaller scale (∼1 km length) than the C2 fans (Fig. 2B; Fig. S2F). The C3 fans cut across the faults and C2 fans. The C3 fans are both smaller and less eroded than the C2 fans, with few craters preserved, but channels are still recognizable on their surfaces. Like the C2 fans, the C3 fans are interpreted as alluvial fans that formed on the canyon floor.

PERCHED SEDIMENT FAN DEPOSITS

The canyon walls of southeastern Coprates Chasma show a highly rugged topography characterized by spur and gully features. However, on both the north and south walls, we observe a set of relatively low-gradient, planar surfaces forming discontinuous patches (Fig. 2C) that are perched as high as 4 km above the canyon floor, coincident with a slope break along the deeply eroded canyon walls (Fig. 1). These remnant surfaces or terraces are ∼5 km in length with slopes of 6°–11° (Table S1). These terraces commonly emerge and radiate out from the termination of gullies (clustered at −200 ± 200 m elevation). The terrace surfaces are highly degraded, containing many impact craters, but erosional channels and ridge structures are still recognizable on some surfaces (Fig. 2C). The ridges are similar to the inverted fluvial channel deposits found on the C2 fan surfaces. At the eroded edges of the terraces, layering consistent with a sedimentary origin is well exposed (Fig. 2C). At their basinward margin, the terraces terminate abruptly and pass into gullied terrain that extends to the canyon floor and the C2 fans. The eroded distal edges are consistently vertically offset by ∼2 km from the canyon floor (Fig. 1). Like the C2 fans, the terraces themselves are cut by linear, west-east–trending topographic offsets (Fig. 2C; 10–20 m vertical offset).

We interpret the terraces as sedimentary deposits perched on the margins of the canyon walls and further interpret them as the degraded remnants of formerly more extensive and earlier formed sediment fan deposits (herein referred as C1 fans). The sedimentary layering exposed in terrace edges suggests that these are sedimentary deposits as opposed to planar surfaces cut into bedrock. The morphology of the terraces is similar to that of the C2 fans: erosional channels and inverted fluvial channels are present on their surfaces, and the terraces radiate outwards from the termination of gullies and with comparable surface slopes. These eroded sediment fan deposits occur at similar elevation planes (apices: −200 ± 200 m) along a 70 km canyon section, suggesting that they originally formed at the former elevation of the canyon floor (Fig. 1A). We interpret these offsets as arising from normal faulting, although both the fault scarp and sediment fan deposits are now highly degraded (Fig. 2C). In HiRISE

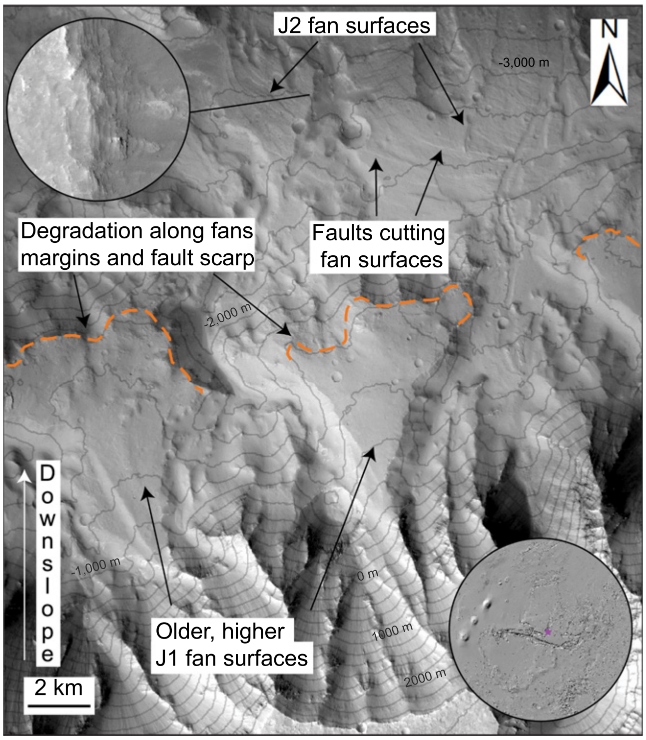

Figure 3. Context Camera (CTX) image of two generations of perched terraces (J1, J2), interpreted as former alluvial fan deposits, on the southern wall of Juventae Chasma, Mars. Eroded distal margins of J1 fans (orange line) may coincide with degraded fault scarp. Both generations of fans are cut by intra-fan faults. Topographic contour interval is 200 m. Top inset shows sedimentary layering in fan margins.

images, sedimentary deposits are also widely visible between the elevations of the C1 and C2 fans, possibly a combination of eroded C1 fan material and an underlying sedimentary basement (Fig. 1; Fig. S5).

SEDIMENT FANS IN JUVENTAE CHASMA

A similar array of perched terrace remnants is observed on the southern wall of Juventae Chasma (Fig. 3; Figs. S6–S7). Two generations of terraces are visible: an upper set (commencing at −850 ± 160 m elevation, 4–9 km length; J1) and a lower, stratigraphically younger set (commencing at −2400 ± 90 m elevation, 5–10 km length; J2). Both generations of terrace remnants share a similar morphology: they radiate outwards in the downslope direction, contain erosional channels and inverted channel deposits (Figs. S7B and S7C), have low-gradient surfaces (5°–7°; Table S1), and are cut by linear west-east– and northwest-southeast–trending topographic offsets (Fig. S7D). Layering consistent with a sedimentary origin is visible in scarps at their lateral and distal margins (Fig. 3). The distal margins of the J1 and J2 terraces are 2400 m and 600 m above the current canyon floor, respectively. As in southeastern Coprates Chasma, we interpret the J1 and J2 terraces as degraded remnants of sediment fan deposits, which originally formed at or near the former canyon floor elevation. We interpret the topographic offset between the J1 and J2 fans as arising from normal faulting, the original fault scarp having since been degraded.

SYN-TECTONIC SEDIMENTATION IN SOUTHEASTERN COPRATES CHASMA AND JUVENTAE CHASMA

The presence of uplifted low-relief terraces on the flanks of southeastern Coprates Chasma and Juventae Chasma, which we interpret as relict sediment fan deposits displaced by faulting, points to a protracted history of differential normal fault slip during growth of these Valles Marineris canyons (Fig. 4; Fig. S8; Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000). In southeastern Coprates Chasma, the preexisting highland terrain (4300 m elevation) appears to have been faulted with throw of ∼5 km to form the initial canyon. The fault scarps defining the canyon flanks were eroded into spur and gully features, with sediment fans (C1 fans; apices −200 m elevation) forming at the mouths of drainages and building out onto the former canyon floor. Continued activity on the canyon-bounding faults led to displacement of the C1 fans and their abandonment, with fan deposits preserved as a set of perched terraces (low-gradient, planar upper surfaces).

The preservation of the fans perched on the flanks of the canyon walls indicates that fault activity may have migrated basinward into the original hanging wall through time (Fig. 4; Fig. S5). Fault displacement shifted to a new set of faults, leaving the C1 fans perched ∼2 km above the canyon floor on the footwall of the new generation of faults. The original C1 fans are now only partially preserved in extent due to extensive degradation (Fig. 2C). Sedimentation at the mouths of drainages, formed due to degradation of the new set of basinward fault scarps, subsequently led to formation of the C2 fans on the current canyon floor (apices −2470 m elevation). The C2 fans have themselves subsequently been faulted by minor synthetic faults (10–50 m throw). Finally, the C3 fans formed near the C2 fan apices, cutting across both the C2 fans and the faults. Alternatively, displacement may have occurred along a canyon-bounding fault zone (aligned with C2 and C3 fan apices). In this scenario, the C1 fans originally formed at or near the canyon floor before fan apices retreated upslope into the footwall during periods of tectonic quiescence. Subsequent displacement along the fault zone led to the C1 fans being left abandoned, perched on the footwall. The southern wall of Juventae Chasma likely developed in a similar manner, with discrete episodes

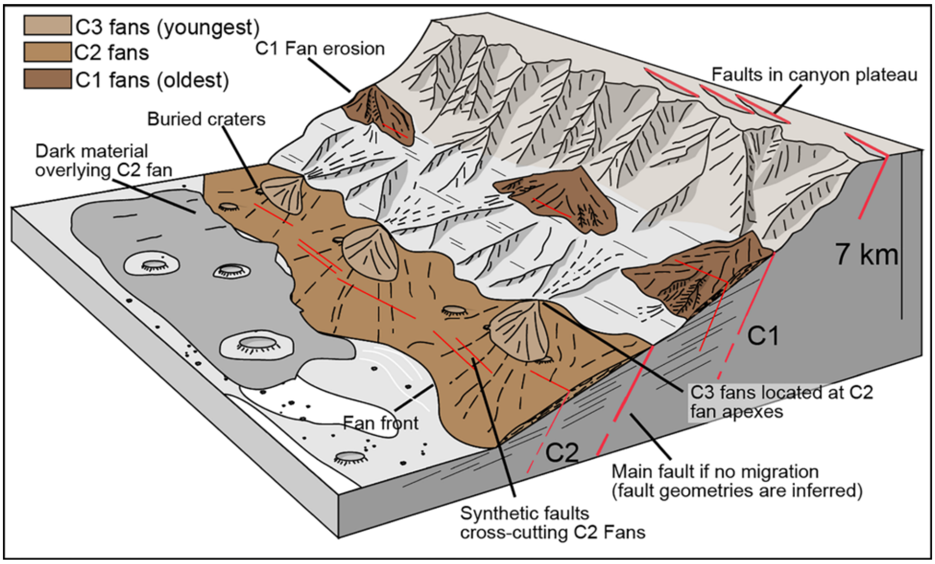

Figure 4. Simplified sketch of the southeastern Coprates Chasma (Mars) showing multiple generations of alluvial fan deposits, which record the syn-tectonic evolution of basin.

of sedimentation and faulting enabling at least two generations of fan deposits (J1 and J2) to form as the canyon deepened. As in southeastern Coprates Chasma, these fan deposits were progressively abandoned and left relatively uplifted as perched terraces due to continued normal faulting.

Both basins show similarities to extensional basins on Earth such as the Gulf of Corinth, where faults migrated basinward through sedimentary deposits (Ford et al., 2013; Goldsworthy and Jackson, 2001; Malartre et al., 2004), and the Black Mountain fault zone (California, USA), where alluvial deposits have been uplifted along a fault zone (Blair, 1999). Geophysical models suggest that the Valles Marineris canyons developed by displacement along near-vertical normal faults, with only modest tectonic extension (Andrews-Hanna, 2012a, 2012b). Vertical separation of different alluvial fan generations by steep normal faulting indicates that multiple periods of syn-tectonic sedimentation occurred during the protracted evolution of the basins. The occurrence of multiple phases of discrete alluvial fan deposition demonstrates that fluvial processes have been active at least sporadically during the tectonic evolution of these basins. This tectonic evolution involved the basinward migration of fault activity or fan apex retreat into the footwall of a fault zone, enabling multiple generations of structurally offset alluvial fans to be preserved. The underfilling of both basins indicates that basin subsidence outpaced the ability of climatically modulated erosion and sediment production in the catchment to infill the basin. Our results suggest that depositional cyclicity was linked to tectonic deformation in at least two canyons, which may be representative of regional processes throughout Valles Marineris.

ACKNOWLEDGMENTS

We acknowledge UK Space Agency funding: grants ST/R002355/1 and ST/V002678/1 (J. Davis, P. Grindrod); ST/S001506/1 (S. Banham); and ST/S001492/1 (S. Gupta). We thank E. Kite, S. Wilson, and L. Matalesta for constructive reviews. We thank the various Mars instrument science and engineering teams for their consistent and dedicated work.

REFERENCES CITED

Anderson, R.C., Dohm, J.M., Golombek, M.P., Haldemann, A.F.C., Franklin, B.J., Tanaka, K.L., Lias, J., and Peer, B., 2001, Primary centers and secondary concentrations of tectonic activity through time in the western hemisphere of Mars: Journal of Geophysical Research, v. 106, p. 20,563–20,585, https://doi.org/10.1029/2000JE001278.

Andrews-Hanna, J.C., 2012a, The formation of Valles Marineris: 1. Tectonic architecture and the relative roles of extension and subsidence: Journal of Geophysical Research, v. 117, E03006, https://doi.org/10.1029/2011JE003953.

Andrews-Hanna, J.C., 2012b, The formation of Valles Marineris: 3. Trough formation through super-isostasy, stress, sedimentation, and subsidence: Journal of Geophysical Research, v. 117, E06002, https://doi.org/10.1029/2012JE004059.

Blair, T.C., 1999, Cause of dominance by sheetflood vs. debris-flow processes on two adjoining alluvial fans, Death Valley, California: Sedimentology, v. 46, p. 1015–1028, https://doi.org/10.1046/j.1365-3091.1999.00261.x.

Blair, T.C., and McPherson, J.G., 1994, Alluvial fan processes and forms, *in* Abrahams, A.D., and Parson, A.J., eds., Geomorphology of Desert Environments: Dordrecht, Springer, p. 354–402, https://doi.org/10.1007/978-94-015-8254-4_14.

Davis, J.M., Balme, M., Grindrod, P.M., Williams, R.M.E., and Gupta, S., 2016, Extensive Noachian fluvial systems in Arabia Terra: Implications for early Martian climate: Geology, v. 44, p. 847–850, https://doi.org/10.1130/G38247.1.

Davis, J.M., Grindrod, P.M., Fawdon, P., Williams, R.M.E., Gupta, S., and Balme, M., 2018, Episodic and declining fluvial processes in southwest Melas Chasma, Valles Marineris, Mars: Journal of Geophysical Research: Planets, v. 123, p. 2527–2549, https://doi.org/10.1029/2018JE005710.

Fassett, C.I., and Head, J.W., 2008, The timing of martian valley network activity: Constraints from buffered crater counting: Icarus, v. 195, p. 61–89, https://doi.org/10.1016/j.icarus.2007.12.009.

Ford, M., Rohais, S., Williams, E.A., Bourlange, S., Jousselin, D., Backert, N., and Malartre, F., 2013, Tectono-sedimentary evolution of the western Corinth rift (Central Greece): Basin Research, v. 25, p. 3–25, https://doi.org/10.1111/j.1365-2117.2012.00550.x.

Gawthorpe, R.L., and Leeder, M.R., 2000, Tectono-sedimentary evolution of active extensional basins: Basin Research, v. 12, p. 195–218, https://doi.org/10.1111/j.1365-2117.2000.00121.x.

Goldsworthy, M., and Jackson, J., 2001, Migration of activity within normal fault systems: Examples from the Quaternary of mainland Greece: Journal of Structural Geology, v. 23, p. 489–506, https://doi.org/10.1016/S0191-8141(00)00121-8.

Grant, J.A., and Wilson, S.A., 2011, Late alluvial fan formation in southern Margaritifer Terra, Mars: Geophysical Research Letters, v. 38, L08201, https://doi.org/10.1029/2011GL046844.

Grindrod, P.M., West, M., Warner, N.H., and Gupta, S., 2012, Formation of an Hesperian-aged sedimentary basin containing phyllosilicates in Coprates Catena, Mars: Icarus, v. 218, p. 178–195, https://doi.org/10.1016/j.icarus.2011.11.027.

Grindrod, P.M., Warner, N.H., Hobley, D.E.J., Schwartz, C., and Gupta, S., 2018, Stepped fans and facies-equivalent phyllosilicates in Coprates Catena, Mars: Icarus, v. 307, p. 260–280, https://doi.org/10.1016/j.icarus.2017.10.030.

Harvey, A.M., 1997, The role of alluvial fans in arid-zone fluvial systems, *in* Thomas, D.S.G., ed., Arid Zone Geomorphology: Process, Form and Change in Drylands (second edition): Chichester, UK, Wiley, p. 231–259.

Kite, E.S., Sneed, J., Mayer, D.P., and Wilson, S.A., 2017, Persistent or repeated surface habitability on Mars during the late Hesperian–Amazonian: Geophysical Research Letters, v. 44, p. 3991–3999, https://doi.org/10.1002/2017GL072660.

Kite, E.S., Mayer, D.P., Wilson, S.A., Davis, J.M., Lucas, A.S., and de Quay, G.S., 2019, Persistence of intense, climate-driven runoff late in Mars history: Science Advances, v. 5, eaav7710, https://doi.org/10.1126/sciadv.aav7710.

Leeder, M.R., and Gawthorpe, R.L., 1987, Sedimentary models for extensional tilt-block/half-graben basins, *in* Coward, M.P., et al., eds., Continental Extensional Tectonics: Geological Society [London] Special Publication 28, p. 139–152, https://doi.org/10.1144/GSL.SP.1987.028.01.11.

Malartre, F., Ford, M., and Williams, E.A., 2004, Preliminary biostratigraphy and 3D geometry of the Vouraikos Gilbert-type fan delta, Gulf of Corinth, Greece: Comptes Rendus Geoscience, v. 336, p. 269–280, https://doi.org/10.1016/j.crte.2003.11.016.

Malin, M.C., et al., 2007, Context Camera Investigation on board the Mars Reconnaissance Orbiter: Journal of Geophysical Research, v. 112, E05S04, https://doi.org/10.1029/2006JE002808.

McEwen, A.S., et al., 2007, Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE): Journal of Geophysical Research: Planets, v. 112, p. 1–40, https://doi.org/10.1029/2005JE002605.

Moore, J.M., and Howard, A.D., 2005, Large alluvial fans on Mars: Journal of Geophysical Research, v. 110, E04005, https://doi.org/10.1029/2004JE002352.

Morgan, A.M., Howard, A.D., Hobley, D.E.J., Moore, J.M., Dietrich, W.E., Williams, R.M.E., Burr, D.M., Grant, J.A., Wilson, S.A., and Matsubara, Y., 2014, Sedimentology and climatic environment of alluvial fans in the martian Saheki crater and a comparison with terrestrial fans in the Atacama Desert: Icarus, v. 229, p. 131–156, https://doi.org/10.1016/j.icarus.2013.11.007.

Murchie, S., et al., 2007, Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO): Journal of Geophysical Research, v. 112, E05S03, https://doi.org/10.1029/2006JE002682.

Palucis, M.C., Dietrich, W.E., Hayes, A.G., Williams, R.M.E., Gupta, S., Mangold, N., Newsom, H., Hardgrove, C., Calef, F., III, and Sumner, D.Y., 2014, The origin and evolution of the Peace Vallis fan system that drains to the Curiosity landing area, Gale Crater, Mars: Journal of Geophysical Research: Planets, v. 119, p. 705–728, https://doi.org/10.1002/2013JE004583.

Sarkar, R., Edgett, K.S., Ghosh, D., Porwal, A., and Singh, P., 2019, Tectonic evolution of Juventae Chasma, Mars, and the deformational and depositional structural attributes of the four major light-toned rock exposures therein: Icarus, v. 333, p. 199–233, https://doi.org/10.1016/j.icarus.2019.05.032.

Warner, N.H., Sowe, M., Gupta, S., Dumke, A., and Goddard, K., 2013, Fill and spill of giant lakes in the eastern Valles Marineris region of Mars: Geology, v. 41, p. 675–678, https://doi.org/10.1130/G34172.1.

Weitz, C.M., Milliken, R.E., Grant, J.A., McEwen, A.S., Williams, R.M.E., and Bishop, J.L., 2008, Light-toned strata and inverted channels adjacent to Juventae and Ganges chasmata, Mars: Geophysical Research Letters, v. 35, L19202, https://doi.org/10.1029/2008GL035317.

Williams, R.M.E., Zimbelman, J.R., and Johnston, A.K., 2006, Aspects of alluvial fan shape indicative of formation process: A case study in southwestern California with application to Mojave Crater fans on Mars: Geophysical Research Letters, v. 33, p. 2–5, https://doi.org/10.1029/2005GL025618.

Wilson, S.A., Morgan, A.M., Howard, A.D., and Grant, J.A., 2021, The global distribution of craters with alluvial fans and deltas on Mars: Geophysical Research Letters, v. 48, e2020GL091653, https://doi.org/10.1029/2020GL091653.

Printed in USA