Geology

Retreat of a giant cataract in a long-lived (3.7–2.6 Ga) martian outflow channel

Nicholas H. Warner, Sanjeev Gupta, Jung-Rack Kim, Shih-Yuan Lin and Jan-Peter Muller

Geology 2010;38;791-794
doi: 10.1130/G31268.1

Notes

THE GEOLOGICAL SOCIETY OF AMERICA

Retreat of a giant cataract in a long-lived (3.7–2.6 Ga) martian outflow channel

Nicholas H. Warner[1*], Sanjeev Gupta[1], Jung-Rack Kim[2], Shih-Yuan Lin[2], and Jan-Peter Muller[2]
[1]Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[2]Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Holmbury St Mary, Surrey RH5 6NT, UK

ABSTRACT

We describe the evolution of an ~600-m-deep tributary outflow channel to Ares Vallis, Mars. High-resolution topography, image analysis, and crater statistics indicate that this tributary canyon developed by the upstream migration of a large, ~300-m-tall cataract during multiple flood events that span ~1 b.y. of Mars history (3.7–2.6 Ga). Issuing from Hydapsis Chaos, these floods were initiated at a similar time and occurred over a similar time range to flooding in Ares Vallis, suggesting a potential regional control on flood initiation and chaos formation. In addition, we provide evidence that cataract retreat and significant incision within the tributary canyon occurred only after a series of downcutting events within Ares Vallis. Topography data and crater statistics taken from the floor of Ares Vallis indicate an ~300 m base-level drop that coincides temporally with an Early Amazonian (ca. 2.6 Ga) flood event and cataract formation within the tributary canyon. The results both confirm the hypothesis of long-term, multiple flood events within martian outflow channels and demonstrate the influence of base-level change on their incision.

INTRODUCTION

Giant outflow channels, interpreted to have been carved by catastrophic water floods derived from confined subsurface aquifers, are well documented on the surface of Mars (Baker, 1982; Carr, 2007; Burr et al., 2009). These enormous channels, although reasonably well studied, still elicit fundamental questions as to their origin and evolution. How was channel incision initiated? How did the channels erode through time? Were they carved by multiple flood episodes? When were they carved? Addressing these questions is of great significance to reconstructing the evolution of the martian hydrologic cycle because these channels record the largest movements of surface water on the planet (Carr and Head, 2009).

It is difficult to reconstruct the evolution of the outflow channels from preserved geomorphology because prior stages in channel erosion are only partially preserved. Here we take advantage of the preservation of the fossilized remnant of a giant cataract midway along a tributary to Ares Vallis outflow channel (Pacifici et al., 2009). Cataracts are abrupt discontinuities in the longitudinal profiles of flood-eroded channels and record the upstream retreat of a wave of streambed erosion. They thus represent frozen transient landforms, capturing a phase in the evolution of the channel. Spectacular examples of cataracts associated with megafloods exist on Earth, such as the Missoula and Bonneville floods (Bretz, 1932; Malde, 1968; Baker, 1982; O'Conner, 1993). The most famous of these is Dry Falls, a 120-m-high, 5.5-km-wide cataract complex in Grand Coulee, a large flood-eroded canyon in the Channeled Scabland of western Washington State, United States (Bretz, 1932; Bretz et al., 1956). Bretz argued that canyons downstream of Dry Falls were carved by headward recession of this cataract complex (Bretz, 1932; Bretz et al., 1956).

Here we combine new image and topography data with high-resolution crater statistics to reconstruct the evolution of the giant martian cataract. We posit that cataract initiation, retreat, and vertical incision within the tributary canyon to Ares Vallis were triggered by drops in base level at its mouth, a direct result of progressive incision of the main branch of Ares Vallis during a period of long-lived episodic flooding within both flood systems. Our results shed light on mechanisms of erosion and evolution of the martian outflow channels and provide an important data point for the assessment of long-term hydrologic activity from two independent flood sources in the planet's equatorial regions.

METHODS

To describe the tributary channel system, we analyze the European Space Agency's Mars Express High Resolution Stereo Camera (HRSC) digital terrain models (DTMs) (75 m grid spacing) and HRSC orthoimages (12 m pixel^{-1}), and the National Aeronautics and Space Administration's Mars Reconnaissance Orbiter high-resolution Context Camera (CTX) images (6 m pixel^{-1}), derived CTX DTMs (18 m grid spacing), and High Resolution Imaging Science Experiment (HiRISE) images (25 cm pixel^{-1}) (see the GSA Data Repository[1]) (Kim and Muller, 2009; Lin et al., 2010).

GEOLOGIC SETTING

Ares Vallis extends for ~2000 km from its source at Iani Chaos–Margaritifer Chaos to its mouth within Chryse Planitia (Fig. DR3 in the Data Repository) (Baker, 1982). In its medial reach, Ares Vallis is a single 30-km-wide, 1.2-km-deep bedrock channel (Fig. 1) (Komatsu and Baker, 1997; Pacifici et al., 2009; Warner et al., 2009). The target tributary canyon in this analysis, located at 8°N, 336°E, is a northwest-

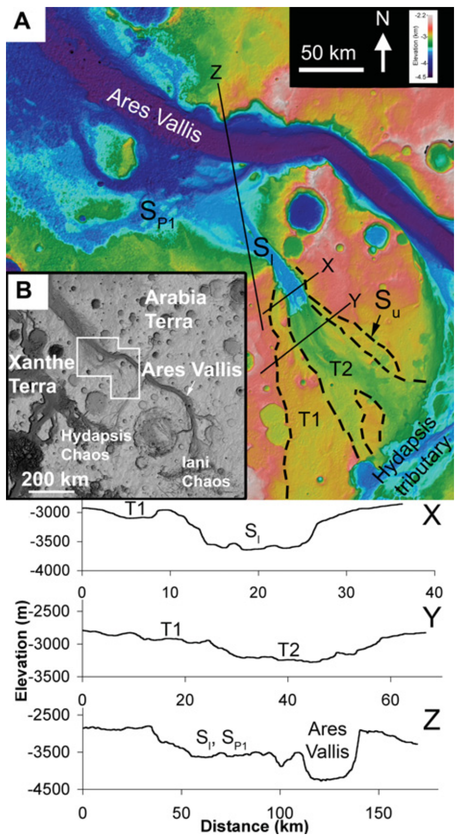

Figure 1. A: High-Resolution Stereo Camera color-shaded digital terrain model with associated profiles at 75 m grid spacing showing the medial region of Ares Vallis and the tributary canyon. Tributary canyon is centered at 8°N, 336°E. Upper flood surface (S_u) shows evidence for at least two flood surfaces (T1, T2) that are derived from floods at Hydapsis Chaos. Lower surface of tributary canyon (S_l) is confluent with perched flood channel in Ares Vallis (S_{P1}). B: Regional context image displaying Ares Vallis outflow channel and the bordering highland terrains of Xanthe Terra and Arabia Terra.

*E-mail: n.warner@imperial.ac.uk.

[1]GSA Data Repository item 2010223, methods, Figures DR1–DR6, and Table DR1, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

southeast–trending linear feature that is sourced by Hydapsis Chaos and cuts through the Xanthe Terra highland terrain before it joins with Ares Vallis (Fig. 1). It is subdivided into two reaches, the upper canyon (S_u) and the lower canyon (S_l), by a prominent 300-m-high cataract (Fig. 2). At its upstream end, a deeply incised northeast-southwest–trending outflow channel that is also derived from Hydapsis Chaos beheads the canyon. Within the canyon, geomorphic features such as streamlined islands and longitudinal grooves provide evidence that it was eroded by catastrophic floodwaters (Komatsu and Baker, 1997; Pacifici et al., 2009; Warner et al., 2009).

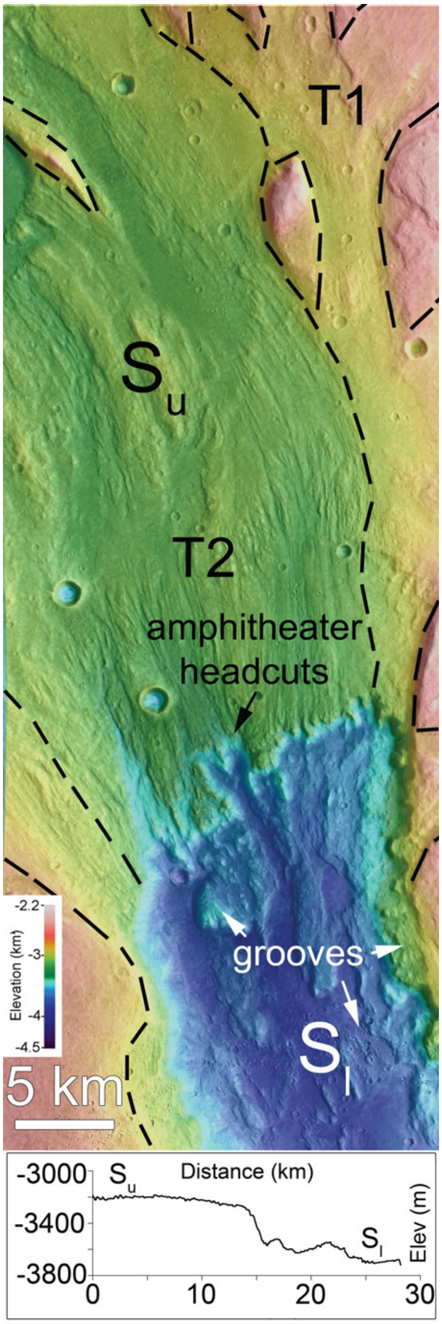

Figure 2. Context camera (CTX) color-shaded digital terrain model at 18 m grid spacing overlain on CTX orthoimage displaying cataract, flood surfaces, and topographic profile taken across cataract along strike of tributary canyon. S_u—upper flood surface; S_l—lower surface of tributary canyon; T1, T2—flood surfaces (derived from floods at Hydapsis Chaos).

TOPOGRAPHY AND GEOMORPHOLOGY OF THE TRIBUTARY CANYON

Upper Canyon

The broad canyon upstream of the cataract (S_u) is several tens of kilometers wide and is incised as much as 450 m into cratered plains material. The basal surface of the canyon contains multiple sets of intersecting and truncating subparallel grooves, streamlined bedrock remnants, and streamlined impact craters. The grooves originate from Hydapsis Chaos and converge at the cataract downstream (Fig. 2). The HRSC and CTX topography data indicate that the grooved surfaces occur at varying elevations (Fig. 1). The lowermost surface (T2), at an average elevation of –3220 m, composes a broad channel that has a maximum depth of 300 m, is wide as 30 km, and has a slope of ~0.3°. The well-defined grooves on this surface are on average 150 m wide and are spaced by ~200 m (Fig. 2). The inner channel is flanked on either side by a bedrock terrace (Fig. 1). The upper terrace (T1) is best defined along the southwestern margin of the inner channel at an elevation of –2880 m and represents the extent of an earlier broad (~70-km-wide), shallow (~150-m-deep) flood surface. A prominent perched channel ~4 km wide and ~160 m deep extends from T1 ~20 km downstream of the cataract, indicating that floods originally carved a broad, but relatively shallow channelized surface where the lower canyon is now present.

Cataract

The cataract is an ~300-m-high headwall that is ~15 km wide, and has a maximum slope of 20°. It has a crenulated face that is etched by a series of 200 m to 1 km diameter amphitheater-shaped headcuts that erode back into S_u by as much as 4 km (Fig. 2; Fig. DR4). Individual headcuts also appear to connect to erosional grooves on S_u. The local bedrock lithology is probably composed of layered basaltic lavas and impact breccias (Rotto and Tanaka, 1995; Nelson and Greeley, 1999; Rogers et al., 2005; Tanaka et al., 2005). These lithologies are likely well jointed and prone to toppling failure to preserve the cataract face (Lamb and Dietrich, 2009), although evidence of jointing and fracturing cannot be observed in CTX and HiRISE imagery.

Lower Canyon

The lower canyon downstream of the cataract (S_l) forms a 15-km-wide, 90-km-long, and 600-m-deep box canyon incised into bedrock (Fig. 1). Grooved surfaces on the upper edges of the canyon are remnants of the former channel floor, prior to upstream cataract retreat and incision of S_l (Fig. 2). The canyon floor shows a series of subparallel, streamlined bedrock remnants; however, between these remnants, the floor is smooth, lacking evidence for well-developed, continuous longitudinal grooves. The channel floor has a slope of 0.07°. In its distal reach, S_l is confluent with a broad (70-km-wide), west-east–trending perched flood-eroded channel (S_{Pl}) at the western margin of the main canyon of Ares Vallis (Fig. 1). This channel is ~650 m above the floor of Ares Vallis and ~300 m below S_u at the cataract.

CHRONOLOGY OF FLOOD EROSION AND CATARACT RETREAT

High-resolution crater statistics were obtained from multiple CTX strips (6 m pixel^{-1}) covering the tributary canyon to constrain the timing of floods on S_u and S_l (see Table DR1 and the methods section in the Data Repository). Figure 3 illustrates crater cumulative frequency curves for S_u, S_l, and the non-flood-modified highland terrain.

The curve for S_u (Fig. 3A) shows two distinct kinks in the slope from the established chronology functions. This pattern of abrupt slope change is indicative of rapid crater resurfacing, by either burial or erosion (Hartmann and Neukum, 2001; Hartmann, 2005). Given the morphologic evidence for flood grooves, streamlined remnants, and terraced channels, the two kinks in the data likely indicate two erosional resurfacing events. Analysis of CTX images reveals that pre-flood craters are present only on S_u. These craters are among the largest impact features (diameter, D > 2 km), have highly subdued rims, are superimposed by flood grooves, and exhibit streamlined continuous ejecta blankets (Fig. DR5). The cumulative frequency curve indicates a close fit to the ca. 3.9 Ga isochron for D > 2 km (Fig. 3A). This Late Noachian model age (Hartmann and Neukum, 2001) most likely represents the time of formation of the pre-flood highland surface (Rotto and Tanaka, 1995; Nelson and Greeley, 1999) and matches closely the model age of the non-flood-modified highland cratered terrain that surrounds the tributary channel (Fig. 3C).

At D = 2 km, the slope of the cumulative frequency curve for S_u deviates from the 3.9 Ga isochron, providing a model resurfacing age of ca. 3.7 Ga (Fig. 3A). This Late Noachian–Early Hesperian age represents the first erosional event in the tributary, likely corresponding with erosion on T1, and is consistent with the Early Hesperian (3.6 Ga) initiation of flooding of Ares Vallis (Warner et al., 2009). A second major kink in the cumulative frequency curve occurs at D =

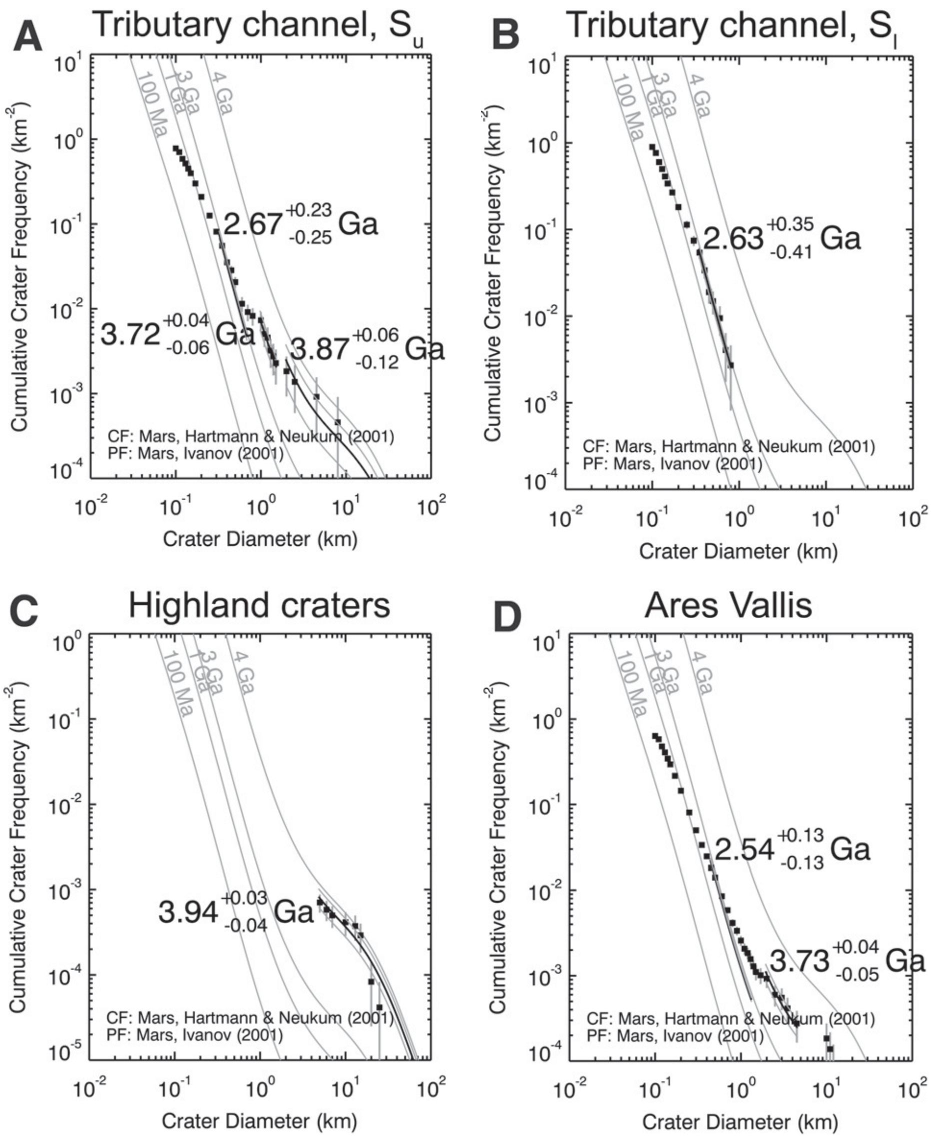

Figure 3. A: Binned cumulative crater frequency histogram for S_u (upper surface of tributary canyon). Curve illustrates pre-flood crater population and two kinks in the fit that represent individual flood resurfacing events. B: Binned cumulative crater frequency histogram for S_l (lower surface of tributary canyon). Crater population on this surface represents last major flood event in tributary. C: Binned cumulative crater frequency histogram of non-flood-modified highland crater terrain. D: Binned cumulative crater frequency histogram for main canyon floor of Ares Vallis. Model resurfacing age on this surface corresponds with last major flooding event within tributary canyon. CF—chronology function; PF—production function.

900 m and is suggestive of a second resurfacing event. For craters with D = 250–700 m, an Early Amazonian model resurfacing age of ca. 2.7 Ga was obtained and represents the time since the last major phase of flood erosion on the tributary surface, possibly corresponding with the formation of T2. We (Warner et al., 2009) also provided an Early Amazonian (2.5–2.9 Ga) model age for final flooding in the proximal main branch of Ares Vallis.

By comparison, S_l lacks craters with D > 900 m and shows no evidence in the cumulative frequency curve for multiple resurfacing events (Fig. 3B). For craters with D = 400–900 m, the curve provides an Early Amazonian model age of 2.6 Ga. We suggest that the last major resurfacing event on S_l corresponds with the Early Amazonian event on S_u.

The absence of a large crater population (D > 900 m) on S_l suggests that flood erosion was responsible for complete resurfacing of the pre-flood impact crater population. However, the preservation of a pre-flood crater population on S_u suggests that the same floods were not capable of complete resurfacing here (Fig. 4). This indicates a significant difference in the rate of vertical incision between the two surfaces, suggesting that major flood erosion of the canyon is accomplished primarily by lateral cataract retreat.

DISCUSSION: CATARACT FORMATION AND CHANNEL EVOLUTION

Cataracts in flood-eroded channels on Earth are commonly initiated at topographic discontinuities; for example, the Dry Falls cataract complex in the Channeled Scabland developed at a structurally controlled slope break (Bretz, 1932). We propose that cataract retreat was initiated by a change in base level at the confluence of the tributary and Ares Vallis, during a period of long-lived flood activity in both systems. The chronology data indicate that flooding occurred within the tributary channel over ~1 b.y. of Mars history (3.7–2.6 Ga), corresponding closely with the onset and termination of flood activity within Ares Vallis (Warner et al., 2009). The coincidence in timing of the erosion events within Ares Vallis (sourced at Iani Chaos) and the tributary canyon (sourced at Hydapsis Chaos) may suggest a regional mechanism for the initiation and cessation of circum-Chryse floods. Likewise, the chronology implies that local mechanisms (e.g., volcanism) that could have induced the catastrophic release of groundwater at these locations are less plausible, as these events would need to be time synchronous.

It is highly unlikely that continuous flooding could have been sustained for the entire proposed history of the tributary system. However, at least two flood events likely occurred within the tributary as Ares Vallis was downcut. The current floor of Ares Vallis is located ~650 m beneath the floor of S_l, indicating that final incision of Ares Vallis postdates tributary formation. However, HRSC topography data indicate that S_l is graded to the perched channel (S_{P1}) along the western margin of Ares Vallis (Fig. 1).

Figure 3D provides a crater cumulative frequency curve for the deepest surface within the main channel of Ares Vallis, from Iani Chaos to the mouth of the canyon. On the channel floor, impact craters with D < 2 km indicate a model resurfacing age of ca. 2.5 Ga. Given the average error in the model age estimates (±0.13 Ga), the time of final flood erosion in Ares Vallis corresponds closely with and perhaps occurred immediately after the Early Amazonian-age final flood event that eroded S_u and S_l (Fig. 3B). We suggest that cataract retreat and incision that created S_l began due to a base-level drop associated with formation of S_{P1}, within only a few hundred million years of the final base-level drop in Ares Vallis (Figs. 1 and 4). Furthermore, we (Warner et al., 2009) suggested that flooding was initiated within Ares Vallis at 3.6 Ga. The initial 3.7 Ga episode of flooding within the tributary system, likely corresponding with formation of

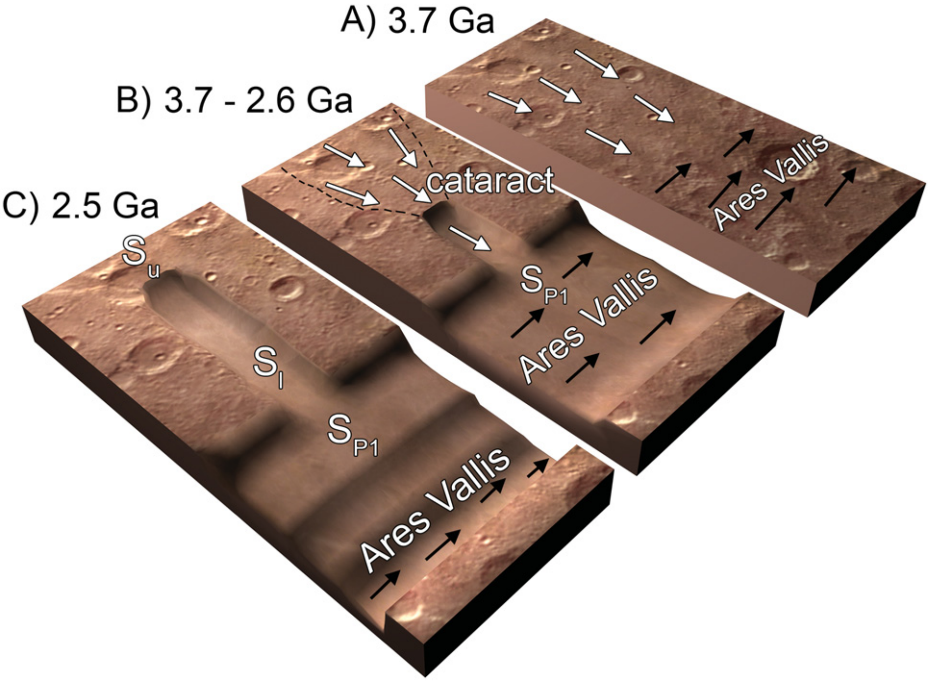

Figure 4. Schematic diagram illustrating sequence of base-level change, cataract migration, and canyon evolution. A: Late Noachian–Early Hesperian overland floods are sourced from Hydapsis Chaos (white arrows) and are confluent with shallow precursor channels of Ares Vallis (black arrows). B: Channelization of Ares Vallis induces base-level change and cataract formation along its west bank, forming lower tributary canyon in Hesperian–Early Amazonian. S_l—lower surface of tributary canyon; S_{P1}—Ares Vallis Perched Channel; Su—upper surface of tributary canyon. C: Progressive downcutting of Ares Vallis isolates tributary canyon and forms perched channels and/or terraces in Early Amazonian. Cessation of flooding in tributary canyon occurs prior to final incision of Ares Vallis near 2.6 Ga.

the highest terrace (T1) on S_u, therefore likely occurred before significant channelization of Ares Vallis, thus supporting the observation of limited downcutting on T1. Cessation of flooding and cataract retreat within the tributary likely occurred by beheading of the channel system as floods from Hydapsis Chaos were rerouted along a new ~50-km-wide, northeast-southwest–oriented channel (Fig. 1).

CONCLUSION

Our results confirm that cataract retreat, controlled by base-level changes within long-lived flood systems, was an important process in the erosion of outflow channels on Mars. By comparison, we speculate that the Noachian age, 1–3-km-tall scarp that bounds the southern margin of the Chryse Basin provided a topographic break that initiated cataract retreat and bedrock incision within the primary circum-Chryse outflow systems (e.g., Ares Vallis, Kasei Valles, Maja Vallis). Furthermore, our results support a new paradigm of martian outflow channel evolution that requires long-lived (~1 b.y.) episodic flood activity (Warner et al., 2009), and suggest a regional mechanism for flood initiation with concurrent groundwater release from Hydapsis Chaos and Iani Chaos at 3.7 Ga.

ACKNOWLEDGMENTS

We thank the High Resolution Stereo Camera (HRSC) teams at the German Aerospace Centre (DLR), Freie Universitat Berlin, and European Space Agency, and the context camera (CTX) and Mars Reconnaissance Orbiter (MRO) teams for making the imagery data available. This research was supported by the UK Science and Technology Facilities Council (grants ST/F003099/1, PP/E00217X/1, PP/E002366/1). Gupta was supported by a Royal Society–Leverhulme Trust Senior Research Fellowship. We thank J. O'Conner and R. Irwin for reviews, L. Wendt for discussion, and J. Simpson and J. Morley for help. We also thank Kristy Barkan of the Academy of Arts (San Francisco) for creating Figure 4.

REFERENCES CITED

Baker, V.R., 1982, The channels of Mars: Austin, University of Texas Press, 198 p.

Bretz, J.H., 1932, The Grand Coulee: New York, American Geographical Society, 89 p.

Bretz, J.H., Smith, H.T.U., and Neff, G.E., 1956, Channeled Scabland of Washington: New data and interpretations: Geological Society of America Bulletin, v. 67, p. 957–1049, doi: 10.1130/0016-7606(1956)67[957:CSOWND]2.0.CO;2.

Burr, D.M., Carling, P.A., and Baker, V.R., 2009, Megaflooding on Earth and Mars: Cambridge, Cambridge University Press, 319 p.

Carr, M.H., 2007, The surface of Mars: Cambridge, Cambridge University Press, 322 p.

Carr, M.H., and Head, J.W., 2009, Geologic history of Mars: Earth and Planetary Science Letters, doi: 10.1016/j.epsl.2009.06.042.

Hartmann, W.K., 2005, Martian cratering 8; isochron refinement and the chronology of Mars: Icarus, v. 174, p. 294–320, doi: 10.1016/j.icarus.2004.11.023.

Hartmann, W.K., and Neukum, G., 2001, Cratering chronology and the evolution of Mars: Space Science Reviews, v. 96, p. 165–194, doi: 10.1023/A:1011945222010.

Ivanov, B., 2001, Mars/Moon Cratering Rate Ratio Estimates: Space Science Reviews, v. 96, p. 87–104.

Kim, J.-R., and Muller, J.-P., 2009, Multi-resolution topographic data extraction from Martian stereo imagery: Planetary and Space Science, v. 57, p. 2095–2112, doi: 10.1016/j.pss.2009.09.024.

Komatsu, G., and Baker, V.R., 1997, Paleohydrology and flood geomorphology of Ares Vallis: Journal of Geophysical Research, v. 102, p. 4151–4160, doi: 10.1029/96JE02564.

Lamb, M.P., and Dietrich, W.E., 2009, The persistence of waterfalls in fractured rock: Geological Society of America Bulletin, v. 121, p. 1123–1134, doi: 10.1130/B26482.1.

Lin, S.Y., Muller, J.-P., Mills, J., and Miller, P., 2010, An assessment of surface matching for the automated co-registration of MOLA, HRSC and HiRISE DTMs: Earth and Planetary Science Letters, doi: 10.1016/j.epsl.2009.12.040 (in press).

Malde, H.E., 1968, The catastrophic late Pleistocene Bonneville flood in the Snake River Plain, Idaho: U.S. Geological Survey Professional Paper 596, 69 p.

Nelson, D.M., and Greeley, R., 1999, Geology of Xanthe Terra outflow channels and the Mars Pathfinder landing site: Journal of Geophysical Research, v. 104, p. 8653–8669, doi: 10.1029/98JE01900.

O'Conner, J.E., 1993, Hydrology, hydraulics, and geomorphology of the Bonneville flood: Geological Society of America Special Paper 274, 83 p.

Pacifici, A., Komatsu, G., and Pondrelli, M., 2009, Geological evolution of Ares Vallis on Mars: Formation by multiple events of catastrophic flooding, glacial and periglacial processes: Icarus, v. 202, p. 60–77, doi: 10.1016/j.icarus.2009.02.029.

Rogers, A.D., Christensen, P.R., and Bandfield, J.L., 2005, Compositional heterogeneity of the ancient Martian crust: Analysis of Ares Vallis bedrock with THEMIS and TES data: Journal of Geophysical Research, v. 110, E05010, doi: 10.1029/2005JE002399.

Rotto, S., and Tanaka, K.L., 1995, Geologic/geomorphic map of the Chryse Planitia region of Mars: U.S. Geological Survey Miscellaneous Investigations Map I-2441, scale 1: 5,000,000.

Tanaka, K.L., Skinner, J.A., and Hare, T.M., 2005, Geologic map of the northern plains of Mars: U.S. Geological Survey Scientific Investigations Map SIM 2888, scale 1:15,000,000.

Warner, N., Gupta, S., Muller, J.P., Kim, J.-R., and Lin, S.-Y., 2009, A refined chronology of catastrophic outflow events in Ares Vallis, Mars: Earth and Planetary Science Letters, v. 288, p. 58–69, doi: 10.1016/j.epsl.2009.09.008.

Manuscript received 31 March 2010
Revised manuscript received 8 April 2010
Manuscript accepted 9 April 2010

Printed in USA