Science AAAS

# A Closer Look at Water-Related Geologic Activity on Mars

A. S. McEwen, *et al.*

*Science* **317**, 1706 (2007);
DOI: 10.1126/science.1143987

REPORT

# A Closer Look at Water-Related Geologic Activity on Mars

A. S. McEwen,[1]* C. J. Hansen,[2] W. A. Delamere,[3] E. M. Eliason,[1] K. E. Herkenhoff,[4] L. Keszthelyi,[4] V. C. Gulick,[5] R. L. Kirk,[4] M. T. Mellon,[6] J. A. Grant,[7] N. Thomas,[8] C. M. Weitz,[9] S. W. Squyres,[10] N. T. Bridges,[2] S. L. Murchie,[11] F. Seelos,[11] K. Seelos,[11] C. H. Okubo,[1] M. P. Milazzo,[1] L. L. Tornabene,[1] W. L. Jaeger,[4] S. Byrne,[1] P. S. Russell,[8] J. L. Griffes,[7] S. Martínez-Alonso,[6] A. Davatzes,[5] F. C. Chuang,[9] B. J. Thomson,[2] K. E. Fishbaugh,[12] C. M. Dundas,[1] K. J. Kolb,[1] M. E. Banks,[1] J. J. Wray[10]

Water has supposedly marked the surface of Mars and produced characteristic landforms. To understand the history of water on Mars, we take a close look at key locations with the High-Resolution Imaging Science Experiment on board the Mars Reconnaissance Orbiter, reaching fine spatial scales of 25 to 32 centimeters per pixel. Boulders ranging up to ~2 meters in diameter are ubiquitous in the middle to high latitudes, which include deposits previously interpreted as fine-grained ocean sediments or dusty snow. Bright gully deposits identify six locations with very recent activity, but these lie on steep (20° to 35°) slopes where dry mass wasting could occur. Thus, we cannot confirm the reality of ancient oceans or water in active gullies but do see evidence of fluvial modification of geologically recent mid-latitude gullies and equatorial impact craters.

A major goal of the Mars Reconnaissance Orbiter (MRO) mission is to better understand the history of water (*1*). The High-Resolution Imaging Science Experiment (HiRISE) is imaging the martian surface at scales of 25 to 32 cm per pixel, with a center color swath that distinguishes major surface materials (dust, sand, rock, or frost) and stereo imaging for topographic studies (*2*, *3*). We highlight three new results concerning the history of water on Mars: (i) the nature of middle- to high-latitude surface deposits and relevance to putative oceans and climate change, (ii) processes forming and modifying the geologically recent gullies, and (iii) evidence for water in the ejecta of recent equatorial impact craters.

The origin of the Vastitas Borealis Formation (VBF), covering the lowest portions of the extensive northern plains, has been the subject of much debate, including (among other hypotheses) that it is the fine-grained residue of an ancient ocean (*4*) or that it represents frozen deposits of sediment-laded water from giant outflow channels (*5*). The more than 200 HiRISE images of this unit show that rocks ranging in size from the limits of resolution (~0.5 m) to ~2 m in diameter are ubiquitous (Fig. 1), except where buried by eolian or airfall materials. Boulders are concentrated around circular structures of probable impact origin, but they are present over most of the VBF at uniform densities. In addition, we have seen no light-toned layered deposits within the VBF; such deposits elsewhere are thought to be of aqueous sedimentary origin (*6*). The boulder distribution and absence of light-toned layered deposits are difficult to reconcile with the hypothesis that the VBF primarily consists of a thick (~100-m) deposit of fine-grained materials deposited from suspended sediments in an ocean (*4*). Either the VBF had a different origin or the combination of impacts and periglacial processes has raised boulders from depth and thoroughly mixed them with overlying materials; viscously relaxed topography (*7*) and ubiquitous polygonal-patterned ground (*8*) may be consistent with such processes.

One hypothesis for the origin of recent mid-latitude gullies is that they formed from the melting of snow deposited during a period of higher orbital obliquity, with remnants of the snow pack still present as "pasted-on" material (*9*). HiRISE has imaged this material at several locations, and the surfaces that it appears on include many boulders (fig. S2). We interpret these materials as rock glaciers: rocky deposits rich in ice, similar to interpretations of debris aprons elsewhere on Mars (*7*). The rockiness is inconsistent with a primary origin as dusty snowfall, unless subsequent processes have modified the deposits, but those deposits are nearly free of impact structures and are likely much younger than the VBF, making such modification unlikely. Note that a thin mantle over many mid-latitude regions (*10*) does still appear fine-grained at HiRISE resolution.

Mid-latitude gullies (*11*) are of great interest because they may indicate that liquid water can reach the surface, even today (*6*, *12*). Key questions are whether liquid water is required to form some of them (and, if so, what is the source of that water) and whether the gully-forming processes are ongoing—even in the present-day climate—rather than being the result of past climates and different insolation geometries. HiRISE images confirm that many gully morphologies on Mars, including braided channels and terraces (Fig. 2), are similar to water-carved features on Earth. Boulders 0.5 to 3 m in diameter are more concentrated in the channels than in surrounding terrains, which is consistent with processes that remove the finer particles. Erosional channels occur on slopes of less than 20° (e.g., Fig. 2, B and C), which is inconsistent with dry granular flows. We are not aware of common terrestrial processes besides running water that could explain all of these observations. HiRISE images also reveal a range of relative ages for the gullies [see the supporting online material (SOM)].

Evidence for ongoing gully activity has come from observations at two locations of new, bright deposits corresponding to depositional fans (*12*) (Fig. 3 and fig. S2). Not all bright deposits at gully termini consist of recent gully-emplaced sediment, as some appear to consist of rippled eolian deposits or patterned ground, modifying relatively old gully deposits (fig. S3).

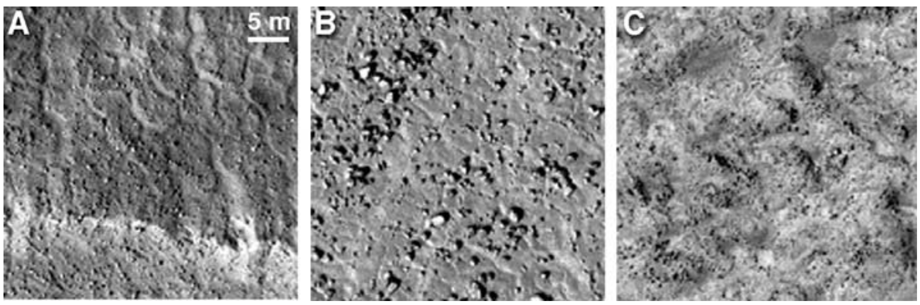


**Fig. 1.** Boulders over northern lowland terrains. (**A**) PSP_001964_2275 (*26*) at 47.0° N, 101.8° E. (**B**) TRA_000846_2475 at 67.0° N, 0.0° E. (**C**) PSP_001810_2175 at 37.2° N, 348.0° E. For all figures, North is at the top and time of day is near 3 p.m., and images have been reprojected to a scale of 25 cm per pixel.

[1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [2]Jet Propulsion Laboratory, Pasadena, CA 91109, USA. [3]Delamere Support Systems, Boulder, CO 80304, USA. [4]U.S. Geological Survey, Flagstaff, AZ 86001, USA. [5]NASA Ames Research Center/SETI Institute, Moffett Field, CA 94035, USA. [6]University of Colorado, Boulder, CO 80309, USA. [7]Smithsonian Center for Earth and Planetary Studies, Washington, DC 20650, USA. [8]University of Bern, Bern, Switzerland. [9]Planetary Science Institute, Tucson, AZ 85719, USA. [10]Cornell University, Ithaca, NY 14853, USA. [11]Applied Physics Laboratory, Laurel, MD 20723, USA. [12]International Space Science Institute, Bern, Switzerland.

*To whom correspondence should be addressed. E-mail: mcewen@lpl.arizona.edu

In the Centauri–Hellas Montes region, the entire equator-facing slope of a crater is covered by narrow gully channels (Fig. 3). There is no evidence for eolian, periglacial, or other modifications of many of these channels. The lower portions of some channels do contain ripples of probable eolian origin, and boulder tracks are superimposed over some channels, so there is a range of relative ages. The bright material, deposited between 1999 and 2004 (*12*), emanates from some apparently unmodified gully channels. From stereo imaging (fig. S4), we confirm that, in some places, this bright deposit diverts around topographic obstructions like a fluid and, at the distal end, overtops low hummocks like a landslide. The shape of the deposit has not changed over the 15 months since last imaged by the Mars Orbiter Camera, which suggests that it is not bright because of frost or ice (*13*). Near-infrared spectra (*14*) do not reveal hydrated minerals in the bright deposit, as might be expected from sublimation of salty groundwater (fig. S5). There are bright materials within gullies over much of the slope, so the new deposit may have come from the redeposition of preexisting bright material (Fig. 3 and fig. S2B). Also, dust-sized materials are generally brighter than sand and rocks on Mars. Thus, the relative brightness of this material does not directly indicate a role for water.

We have imaged gully deposits with bright termini at four locations that appear to be very recent, in addition to the two locations reported previously (figs. S6 and S7). These deposits are again associated with fine channels and show no subsequent modification. All six of the deposits are near the base of relatively long, steep slopes (see the SOM, including table S1); five are on the slopes of well-preserved impact craters. There is no favored slope aspect: The bright deposits are on east-, west-, equator-, and pole-facing slopes. All are in the middle latitudes 31° to 47° N and S, but there has been no systematic monitoring of steep slopes in the equatorial regions of Mars, so a latitudinal dependence to active slope movements is unknown. The average slopes are greater than 20°, close to the stability limits of dry, unconsolidated materials, and the elevation drops by at least 500 m (table S1). Long, steep slopes are favorable to both groundwater breakouts and gravity-driven movements. In summary, although the involvement of liquid water cannot be ruled out, there is no confirmation from MRO analyses to date that water reached the surface in the past decade.

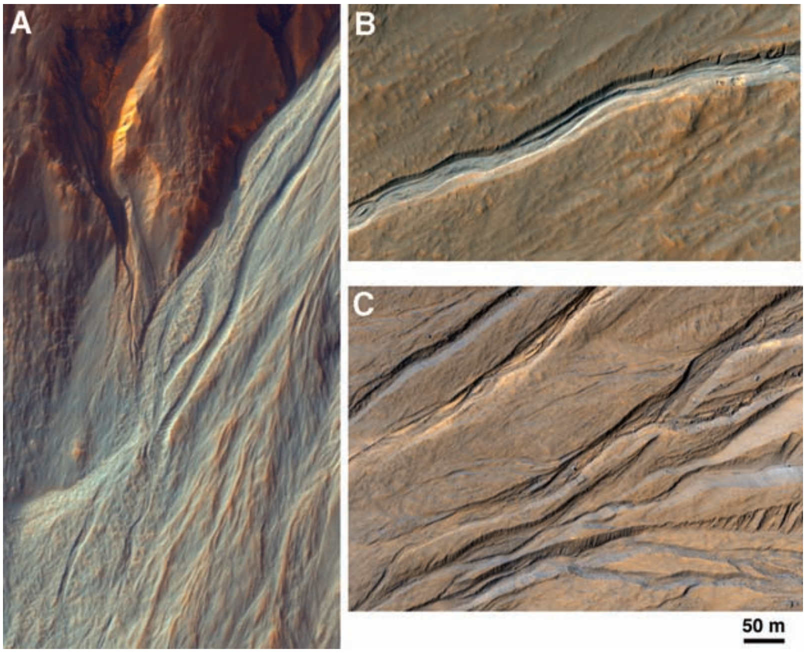


**Fig. 2.** Color images of gully channels. (**A**) Portion of PSP_002172_1410 at 38.9° S, 195.9° E. (**B**) and (**C**) are portions of PSP_002932_1445 at 35.1° S, 324.7° E in Hale Crater. Color (here and in other figures) is constructed from red and blue-green bandpasses and exaggerated as compared with natural color. Downslope direction is toward the bottom of (A) and the lower left of (B) and (C).

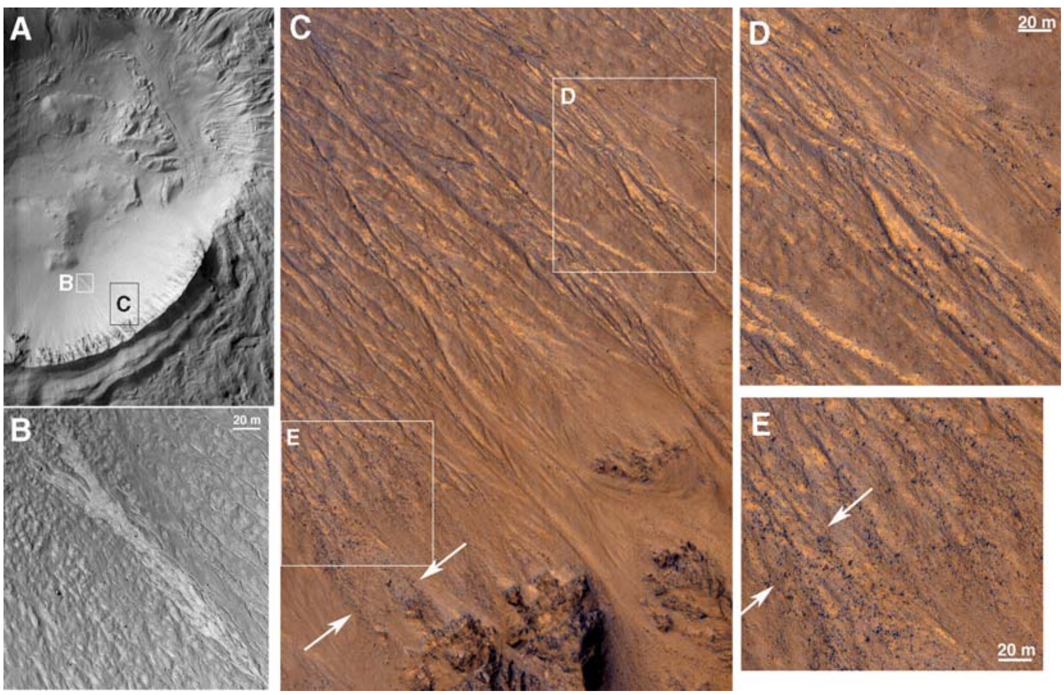


**Fig. 3.** Crater in Centauri–Hellas Montes region at 38.4° S, 96.8° E. (**A**) Browse image PSP_001714_1415. (**B**) Full-resolution portion of image indicated in (A), showing the bright deposit. (**C**) Color for portion of image indicated in (A). (**D**) Enlargement of channels [indicated in (C)], showing eroded bright deposits and boulders concentrated in the channels. (**E**) Enlargement of the apparent source region [indicated in (C)] above the new bright deposit. The shallow depression and uppermost channels leading to the new deposit lie between the arrow tips in (C) and (E). North is 7 degrees to the right of the top.

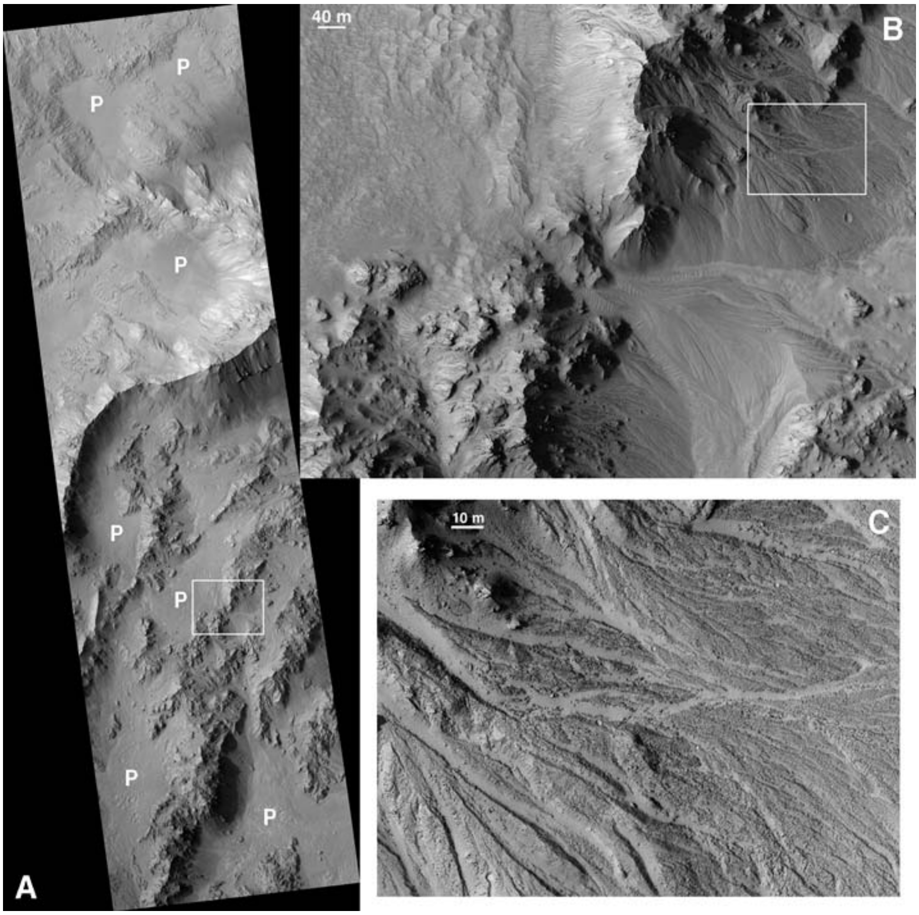


**Fig. 4.** Northwestern rim of Mojave Crater at 7.6° N, 327° E (PSP_001481_1875). (**A**) Full browse image at greatly reduced resolution. Several locations of ponded and pitted material are labeled with "P"; boxed area shows the location of enlargement indicated in (B). (**B**) An example of where a large fan emanates from the ponded and pitted material to the northwest; boxed area shows enlargement to the full-resolution sample indicated in (C). (**C**) Braided and distributary channels and boulders up to ~1 m in diameter.

The lobate morphology of some martian impact crater ejecta has long been considered evidence for fluidization by water (*15*) or other mechanisms (*16*), but conclusive evidence for the presence of water in the ejecta has been elusive (*17*). Meanwhile, another debate has arisen about the possibility of impact-induced "rainfall" producing the erosion of Noachian (>3.7 billion-year-old) terrains (*18*). HiRISE observations of relatively large but geologically recent and well-preserved impact craters are providing insights relative to both debates.

Mojave Crater (60 km in diameter) contains channels and fan-shaped deposits (*11*) with a marked resemblance to alluvial fans in desert regions on Earth (*19*). The branching channels of third or fourth order include first-order channels at topographic peaks and ridges (Fig. 4B), which are difficult to explain by seepage of a groundwater table, leading to the hypothesis of impact-generated precipitation (*20*). The channels and fans are present on much of the terrace and rim regions but not on all topographic features (e.g., the central uplift or ponded and pitted materials), which may prove difficult to reconcile with the precipitation theory. A geologically recent origin of the crater is indicated by the small number of impact craters superimposed on both the fans and undissected portions of the crater (*21*). Mojave appears to be one of the most recent craters on Mars that is larger than 50 km in diameter, which form on average about every 20 million years (*22*). HiRISE stereo observations show ponded materials at various levels inside and outside of the crater (Fig. 4A), which sometimes have a fractured surface similar to ponded materials in lunar craters (*23*). However, unlike lunar examples, the martian "ponds" are often covered by coalesced pits, which lack raised rims and appear to be coeval. We interpret this pitted, ponded unit to be a mix of melt and fragmented rock similar to that found in terrestrial impact craters in volatile-rich targets (*24*), with pitting due to collapse from the loss of volatiles. There is a close association between the ponded material, which does not show evidence for erosion by overland flow, and the channels and fans that extend downhill of the ponded deposits (*25*) (Fig. 4B), suggesting that water was released from the ponded deposits.

The fluvial geomorphology of Mojave Crater was thought to be an isolated occurrence (*19*, *20*), but we have found channels, alluvial-like fans, debris flows, and the presence of ponded and pitted material in other geologically recent craters, including Hale (125 to 150 km in diameter), Tooting (28 km in diameter; fig. S8), Zunil (10 km in diameter), and more than ten others (*25*). The ponded material appears to be far more voluminous than ponded materials in lunar craters of comparable size, in spite of lower primary impact velocities on Mars (i.e., less melt production if the target materials were identical). The key difference may be that the martian upper crust is rich in ice, water, and hydrated minerals, which can form muddy debris and lower the melting point of silicate minerals. The evidence for impact-induced precipitation at Mojave or elsewhere remains inconclusive, but the HiRISE observations demonstrate that landscapes with a fluvially modified appearance may be produced by syndepositional effects during impact cratering. The much larger and more numerous craters produced in the Late Noachian could explain some of the pervasive erosion of Noachian-aged terrains, thus weakening the argument that ancient Mars must have had a warmer, wetter climate on a sustained basis.

HiRISE observations are sharpening our view of when and where water has modified the martian surface. These observations inform models for past and present geologic and climatic processes and can focus future exploration to those locations with the greatest promise for discovering evidence for life.

### References and Notes


1. R. Zurek, S. Smrekar, *J. Geophys. Res.* **112**, E05S01 (2007).
2. A. S. McEwen *et al.*, *J. Geophys. Res.* **112**, E05S02 (2007).
3. C. H. Okubo, A. S. McEwen, *Science* **315**, 983 (2007).
4. M. A. Kreslavsky, J. W. Head, *J. Geophys. Res.* **107**, 5121 (2002).
5. M. H. Carr, J. W. Head, *J. Geophys. Res.* **108**, 5042 (2003).
6. M. C. Malin, K. S. Edgett, *J. Geophys. Res.* **106**, 23429 (2001).
7. S. W. Squyres, S. M. Clifford, R. O. Kuzmin, J. R. Zimbelman, F. M. Costard, in *Mars*, H. H. Kieffer *et al.*, Eds. (Univ. of Arizona Press, Tucson, AZ, 1992), pp. 523–554.
8. M. T. Mellon, *J. Geophys. Res.* **102**, 25617 (1997).
9. P. R. Christensen, *Nature* **422**, 45 (2003).
10. J. F. Mustard, C. D. Cooper, M. K. Rifkin, *Nature* **412**, 411 (2001).
11. Martian gullies have been defined as landforms on relatively steep slopes that may include an alcove, channel, and depositional fan (*6*) and that may form by a variety of processes, such as dry mass wasting, wet debris flows, or running water. The gullies are typically much younger than the landforms that they eroded. The channels and fans seen in large young impact craters are similar in morphology to the gullies but are larger, occur

over shallower slopes, and appear to be the same age as the craters.
12. M. C. Malin, K. S. Edgett, L. V. Posiolova, S. M. McColley, E. Z. Noe Dobrea, *Science* **314**, 1573 (2006).
13. K. E. Williams, O. B. Toon, J. Heldmann, *Geophys. Res. Lett.* **34**, L09204 (2007).
14. S. L. Murchie *et al.*, *J. Geophys. Res.* **112**, E05S03 (2007).
15. M. H. Carr, G. G. Schaber, *J. Geophys. Res.* **82**, 4039 (1977).
16. O. S. Barnouin-Jha, P. H. Schultz, *J. Geophys. Res.* **101**, 21099 (1996).
17. R. M. E. Williams, K. S. Edgett, paper presented at the American Geophysical Union Fall Meeting, abstr. P33B-03, San Francisco, CA, 13 to 17 December 2004.
18. T. L. Segura, O. B. Toon, A. Colaprete, K. Zahnle, *Science* **298**, 1977 (2002).
19. R. M. E. Williams, J. R. Zimbelman, A. K. Johnston, *Geophys. Res. Lett.* **33**, L10201 (2006).
20. R. M. E. Williams, K. S. Edgett, M. C. Malin, *Lunar Planet. Sci.* **XXXV**, abstr. 1415 (Lunar and Planetary Institute, Houston, TX, CD-ROM, 2004).
21. There are four craters that are larger than 100 m in diameter in MRO context image 808_1874, which covers $2.1 \times 10^3$ km$^2$ of the interior and continuous ejecta of Mojave Crater.
22. B. A. Ivanov, *Space Sci. Rev.* **96**, 87 (2001).
23. D. J. Heather, S. K. Dunkin, *Icarus* **163**, 307 (2003).
24. G. R. Osinski, *Meteorit. Planet. Sci.* **41**, 1571 (2006).
25. L. L. Tornabene *et al.*, *Lunar Planet. Sci.* **XXXVIII**, abstr. 1338 (Lunar and Planetary Institute, Houston, TX, CD-ROM, 2004).
26. HiRISE images are identified by the format "mission phase_orbit number_orbital position." Thus, PSP_001468_1535 was acquired in the Primary Science Phase, orbit 1468, and 153.5 degrees from the night-side equator or 26.5°S latitude (MRO travels north over the day side in its orbit).
27. We thank the science, operations, and engineering teams of the HiRISE and MRO projects, whose diligent efforts enabled the results presented here, and also thank the reviewers and editor. For more information about HiRISE and image access, see (http://hirise.lpl.arizona.edu).

**Supporting Online Material**
www.sciencemag.org/cgi/content/full/317/5845/1706/DC1
SOM Text
Figs. S1 to S8
Table S1
References

18 April 2007; accepted 10 August 2007
10.1126/science.1143987

REPORT

# Athabasca Valles, Mars: A Lava-Draped Channel System

**W. L. Jaeger,[1]* L. P. Keszthelyi,[1] A. S. McEwen,[2] C. M. Dundas,[2] P. S. Russell[3]**

Athabasca Valles is a young outflow channel system on Mars that may have been carved by catastrophic water floods. However, images acquired by the High-Resolution Imaging Science Experiment camera onboard the Mars Reconnaissance Orbiter spacecraft reveal that Athabasca Valles is now entirely draped by a thin layer of solidified lava—the remnant of a once-swollen river of molten rock. The lava erupted from a fissure, inundated the channels, and drained downstream in geologically recent times. Purported ice features in Athabasca Valles and its distal basin, Cerberus Palus, are actually composed of this lava. Similar volcanic processes may have operated in other ostensibly fluvial channels, which could explain in part why the landers sent to investigate sites of ancient flooding on Mars have predominantly found lava at the surface instead.

Athabasca Valles is the youngest outflow channel system on Mars (*1*–*3*). It originates at a fissure (part of the Cerberus Fossae), extends southwest for about 300 km, and debouches into a basin named Cerberus Palus (Fig. 1). In most respects, Athabasca Valles resembles the catastrophic flood-carved landscape of the Channeled Scabland in Washington State, with branching channels, streamlined "islands," and dunes interpreted to have formed subaqueously (*2*). However, its floor is remarkably uneroded at the subkilometer scale. These seemingly incongruous attributes have spawned multiple hypotheses, which depict the channel floor as either (i) a flood- or glacial-erosion surface with an uneven sediment cover (*2*, *4*), (ii) the icy or desiccated dregs of sediment-laden floodwaters that froze (*5*, *6*), or (iii) a lava flow that coursed through the channel system and solidified (*7*–*9*). Color and stereo images with high spatial resolution (27 to 117 cm/pixel) acquired by the High-Resolution Imaging Science Experiment (HiRISE) camera onboard the Mars Reconnaissance Orbiter (MRO) spacecraft provide observations that are key to resolving this debate.

[1]Astrogeology Team, U.S. Geological Survey, Flagstaff, AZ 86001, USA. [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [3]Physikalisches Institut, Universität Bern, CH-3012, Bern, Switzerland.

*To whom correspondence should be addressed. E-mail: wjaeger@usgs.gov

HiRISE images sample Athabasca Valles from its source to its terminus, showing a solidified flow within the channels at all locations. On the north (upslope) side of the source region, the flow manifests as numerous thin, arcuate, and overlapping fronts that are concentric to the fissure-vent (Fig. 2). The fronts become progressively younger and smaller (i.e., they step up) with proximity to the fissure. They record the final surges in a waning eruption of low-viscosity fluid from the Cerberus Fossae (fig. S1).

Downstream in the channels, the flow exhibits two distinct textures: polygonal and ridged (*5*, *8*–*10*). The difference between these is surficial; the flowtop crumpled where it is ridged but remained intact where it is polygonal. Furthermore, where the flowtop rifted under tensile stress, discrete rafted plates are preserved. In several channel segments, medial ridged terrain is flanked by polygonal terrain, and the contacts between the two textures are brittle shear zones that accommodated higher flow velocities toward the center of the channel (fig. S2). These shear zones indicate that the surface of the flow was solidifying while its fluid interior continued moving downhill through Athabasca Valles.

The flow receded from its maximum stand before completely solidifying. North of the source region, it appears to have embayed a tectonic ridge while at peak discharge and then draped its flank as the eruption waned (fig. S3). However, a deposit of wind-swept, bright material obscures the stratigraphic relationship. Within Athabasca Valles, polygonal and ridged flow textures reach high onto streamlined "islands" and blanket features previously interpreted to be fluvial bedforms, including the putative subaqueous dunes (fig. S4). At its height, the flow filled and locally overbanked the channel system. Subsequently, its level dropped as fluid drained downstream into the contiguous distal basin of Cerberus Palus, where it ponded and solidified. Current channel topography suggests that, in Athabasca Valles, the flow level receded >50 m from its high stand.

The pivotal question is whether the flow is composed primarily of sediment, ice, or lava, and its answer can be educed from the thousands of ring-mound landforms (RMLs) that occur exclusively on the flow surface. RMLs are a continuum of landforms intermediate to rings and mounds (fig. S5). Various hypotheses for their origin have been advanced, each invoking a specific flow composition. If the RMLs are pingos (ice-cored mounds) in various stages of collapse, the flow is a mixture of sediment and extant ice (*5*, *11*, *12*); if the RMLs are cryophreatic cones formed by the explosive release of flow-entrained volatiles, the flow is sediment that was initially volatile-rich but is now degassed (*13*); and if the RMLs are hydrovolcanic (rootless) cones formed when groundwater heated by the overlying flow vented in steam explosions, the flow is lava (*8*, *9*). HiRISE data allow these divergent hypotheses to be tested.

Topographic information derived from HiRISE stereo image pairs shows that many RMLs are ringed by moats. The moats exhibit a frozen-in evolutionary sequence. Incipient moats have