over shallower slopes, and appear to be the same age as the craters.


2.1 × 103 km2 of the interior and continuous ejecta of the final surges in a waning eruption of low-viscosity fluid from the Cerberus Fossae (fig. S1). 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 nightside equator or 26.5° 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).

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REPORT

Athalassas Valles, Mars: A Lava-Draped Channel System

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Athalassas Valles is a young outlet 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 Athalassas 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 Athalassas 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 landsers sent to investigate sites of ancient flooding on Mars have predominantly found lava at the surface instead.

Athalassas Valles is the youngest outlet 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, Athalassas 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 subasciously (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), (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.

HiRISE images sample Athalassas 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 superficial; the flowtop crumpled where it is ridged but remains intact where it is polygonal. Furthermore, where the flowtop ruffled 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 Athalassas 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 Athalassas 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 Athalassas 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 deduced 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 cryoprecipitate cones formed by the explosive release of water-entained 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 ground-water 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 from HiRISE stereo image pairs shows that many RMLs are rimmed by moats. The moats exhibit a frozen-in evolutionary sequence. Incipient moats have
ring fractures at their perimeters, more-evolved moats have tilted slabs that override their surroundings, and end-stage moats show foundering plates (Fig. 3). Thus, the moats formed in response to loading of a thin, brittle crust underlain by deformable material. The crustal thickness at the time of loading can be directly measured where foundering plates are tilted edge-on, and it is on the order of a few meters.

Relict wakes bounded by levees trail downstream from many RMLs. Some of the wakes are severed where the flowtop rafted apart (Fig. 4A). This establishes that the wakes formed on the solidified surface of an active flow. However, they are not gouges left where the flowtop crumpled against anchored obstacles. Instead, they formed as gas vented from fixed sources at depth, ripping continuous openings through the moving flowtop. In some places, the wakes grade into chains of overlapping RMLs (Fig. 4B). These formed through successive explosions in a process loosely analogous to the construction of the Hawaiian Island chain, where Earth’s crust moved over a fixed magma source, producing a string of volcanoes. Thus, the volatile that caused the explosions was housed beneath, not within, the flow. The RMLs are, therefore, hydrovolcanic cones, and the flow is lava. This conclusion is supported by the spatial distribution of RMLs, which preferentially occur where steam venting should be locally enhanced (fig. S6).

Previous work rejected the hydrovolcanic model on the basis that RMLs modified impact craters (12); however, HiRISE images show that the reverse is true. Impact craters are consistently superimposed on RMLs, indicating that the latter are older (fig. S7). Furthermore, the ejecta from these craters is strewn with boulders, suggesting that the target material is rocky. This is consistent with lava but not with ice, which would sublimate at a rate of $10^1$ to $10^2$ m per million years (14, 15).

Several other data sets support the conclusion that the flow is lava. Although radar mapping from Earth-based radio telescopes cannot resolve Athabasca Valles proper, it shows Cerberus Palus to be exceedingly rough at the decimeter scale (16–18). The backscatter and depolarization values are consistent with blocky lava surfaces (18). Similarly, the Gamma-Ray Spectrometer (GRS) onboard the Mars Odyssey spacecraft showed Cerberus Palus to be among the driest regions on Mars, with a water-equivalent hydrogen abundance (~2 to 5 mass percent) suggestive of minor amounts of hydrated minerals, and no appreciable water ice, in the upper ~1 m (19). Both the Thermal Emission Spectrometer (TES) and the Thermal Emission Imaging System (THEMIS) found that, although the region is overlain by sufficient dust to obscure substrate mineralogy (20, 21), the thermal inertia of Athabasca Valles (typically 300 to 400 J/m$^2$/K$s^{1/2}$) is still above average for Mars (22–24). These thermal inertia values do not have a unique interpretation but are comparable to the Gusev Crater and Viking 1 landing sites, both of which had an abundance of basaltic boulders (23). Collectively, these data point to a dust-coated, hydrogen-poor, rocky surface, which is consistent with lava.

**Fig. 1.** (Top) Mars Orbiter Laser Altimeter (MOLA) shaded relief map of Mars covering 0° to 360°E. (Bottom) THEMIS infrared mosaic draped by colorized MOLA elevation data over Athabasca Valles. Key features are labeled. Black boxes locate the following HiRISE images: (a) PSP_001408_1900 (25), (b) stereo pair PSP_001606_1900 and PSP_002226_1900, (c) stereo pair PSP_001540_1890 and PSP_002371_1890, (d) stereo pair PSP_002938_1890 and PSP_003083_1890, (e) stereo pair PSP_002661_1895 and PSP_003294_1895, and (f) stereo pair PSP_002174_1875 and PSP_002292_1875.

**Fig. 2.** HiRISE image PSP_001408_1900 shows plains north of a fissure vent at the head of an Athabasca Valles tributary. Thin, concentric flow fronts cover the plain. Shadow measurements indicate that the fronts are ~1 m tall. The inset shows rough, and consequently dark, bands at their terminal edges. Illumination is from the left, and north is up in this and all subsequent HiRISE images.
Fig. 3. Anaglyphs from subsections of HiRISE stereo image pairs PSP_001606_1900 and PSP_002226_1900 (A and B) and PSP_001540_1890 and PSP_002371_1890 (C). The thin flowtop cracked, shifted, and founded under the weight of RMLs, producing a continuum of moat morphologies from (A) ring fractures, to (B) tilted plates that jut over the surrounding flow surface, to (C) founded plates exposed edge-on.

Fig. 4. (A) Anaglyph of a subsection of HiRISE stereo image pair PSP_001540_1890 and PSP_002371_1890 showing RMLs with wakes severed along rafted plate boundaries. Compressional ridges cover the plates, and polygonal terrain occupies the interstitial space. (B) Anaglyph of a subsection of HiRISE stereo image pair PSP_002938_1890 and PSP_003083_1890 showing a chain of overlapping RMLs. Cross-cutting relationships indicate that the RMLs within the chain became younger in the upstream direction (yellow arrow).

References and Notes
25. HiRISE images are identified by the format "mission phase_orbit_number_orbital position." For example, PSP_001408_1900 was acquired in the Primary Science Phase, orbit 1408, and 190.0° from the right-side equator or 10°N latitude (MRO travels north of the day side in its orbit).
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REPORT

Meter-Scale Morphology of the North Polar Region of Mars

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Mars’ north pole is covered by a dome of layered ice deposits. Detailed (~30 centimeters per pixel) images of this region were obtained with the High-Resolution Imaging Science Experiment on board the Mars Reconnaissance Orbiter (MRO). Planum Boreum basal unit scarps reveal cross-bedding and show evidence for recent mass wasting, flow, and debris accumulation. The north polar layers themselves are as thin as 10 centimeters but appear to be covered by a dusty veneer in places, which may obscure thinner layers. Repetition of particular layer types implies that quasi-periodic climate changes influenced the stratigraphic sequence in the polar layered deposits, informing models for recent climate variations on Mars.

Planum Boreum (the martian north polar topographic dome) has been stratigraphically divided into the irregularly layered “basal unit” (~3), the classical polar layered deposits (PLD) (~4), and the residual cap, which covers most of the planum and maintains a high albedo throughout the northern summer because of its relatively clean water ice composition (~4, ~5). All of these deposits overlie older materials with a complex history (~6). Recent climate

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