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31. Materials and methods are available as supplementary materials on Science Online.

Martian Fluvial Conglomerates at Gale Crater


Observations by the Mars Science Laboratory Mast Camera (Mastcam) in Gale crater reveal isolated outcrops of cemented pebbles (2 to 40 millimeters in diameter) and sand grains with textures typical of fluvial sedimentary conglomerates. Rounded pebbles in the conglomerates indicate substantial fluvial abrasion. ChemCam emission spectra at one outcrop show a predominantly feldspathic composition, consistent with minimal aqueous weathering of sediments. Sediment was mobilized in ancient water flows that likely exceeded the threshold conditions (depth 0.03 to 0.09 meter, average velocity 0.20 to 0.75 meter per second) required to transport the pebbles. Climate conditions at the time sediment was transported must have differed substantially from the cold, hyper-arid modern environment to permit aqueous flows across several kilometers.

D ecades of spacecraft observations of Mars have revealed abundant evidence for past water flows on the basis of a variety of landforms, including deltas, alluvial fans, valley network comparable to terrestrial river valleys, and giant outflow channels carved by catastrophic floods [e.g., (1–3)]. Although martian landforms commonly possess morphology and scaling relationships similar to their counterparts on Earth, the resolution of satellite images is insufficient to reveal sediment particle size, shape, and sorting patterns. Such detailed sedimentary observations are required to confirm that certain martian landforms derived from fluvial processes and provide critical data to perform paleohydrologic modeling. Before the NASA Mars Science Laboratory (MSL) mission, surface observations on Mars occurred at six locations associated with the Viking, Pathfinder, Mars Exploration Rovers, and Phoenix missions. Collectively, observations from surface instruments showed limited evidence for water transport processes at only two sites. At the Pathfinder landing site, observations of aligned and touching boulders were inferred to reflect the effect imbrication by high-velocity catastrophic floods (4–6). In Meridiani Planum, centimeter-scale cross-lamination at Eagle and Erebus craters was interpreted to have resulted from shallow surface flows (with velocities of a few tenths of a meter per second) within an interaerial dune paleoenvironment (7–9). However, no definitive in situ evidence of a sustained fluvial overland transport system has been encountered by previous landers. The MSL Curiosity rover arrived at equatorial Gale crater on 6 August 2012 UTC (Fig. 1). The final landing ellipse was chosen in part because of its proximity to Aeolis Mons (known informally as Mt. Sharp), the central, 5-km-high layered mound within Gale crater, but also because it was close to a prominent alluvial fan, the Peace Vallis fan (10, 11). During the first 100 sols of the mission, Curiosity traveled ~400 m from its landing site across the Bradbury Rise toward bedrock exposed at Glenelg (12, 13). Here, we analyze a suite of rocks encountered along this traverse based on data acquired by the Mast Camera (Mastcam) and ChemCam instruments (14–16).

Outcrop Characteristics

The surface of Bradbury Rise is characterized by two distinct elements: a rock pavement of loose clasts (17) (fig. S1) and occasional horizontal to subhorizontal blocks with embedded pebbles. Here we focus on the latter component, which is present within a narrow (~5 m) elevation range, displays generally similar characteristics, and is interpreted as exposures of a distinct geologic unit or facies. This facies consists of thin (~0.1 m thick), coherent blocks that appear to have a well-defined base and limited areal extent (~1 m²). Although the contact with subjacent rocks is not directly observed, the slabs typically form protruding ledges that imply that the substrate is finer in grain size or less indurated, and easily erodes.

Multiple outcrops of these pebble-rich rock slabs were observed along the first 275 m traversed by the rover, with high-resolution Mastcam images acquired at three locations: Goulburn, Link, and Hotth (Fig. 1C). Goulburn was exposed at the landing site by thrust impiement scours driven by one of the four pairs of descent engines, which removed unconsolidated regolith and revealed the underlying lithified rock (Fig. S2). At this location, a horizontal rock layer composed of pebbles and an unresled facies component was observed. The other two locations, Link and Hotth, were observed within ~100 m of Goulburn, and displayed tilled, fractured pebble-rich rock slabs with sufficient competency to maintain near-vertical faces (Fig. 2A and Fig.

Crystallographic Data Centre under reference number CCDC 933449.

Supplementary Materials

www.sciencemag.org/cgi/content/full/340/6136/1065/DC1

Materials and Methods

Supplementary Text

Tables S1 to S8

References (34–41)

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Fig. 1. Location of study site. (A) (inset) The Curiosity rover landed on the Aeolis Palus lowlands in northwestern Gale crater [white box corresponds to (B)]. Color topographic map displays elevation values from the Mars Orbiter Laser Altimeter (MOLA) instrument (39). (B) The Peace Vallis fan is characterized by convex topographic contours (black lines; contour interval is 5 m, arrow marks downslope direction) from high-resolution imaging Science Experiment (HiRISE) (40) stereo data. The broad topographic expression of the alluvial fan becomes less distinct downslope of the dashed red line. Sinuous ridges interpreted to record former flow paths (i.e., inverted channels) are mapped in white. Bradbury Landing is marked by yellow star. (C) Curiosity’s route in the first 100 sols across Bradbury Rise from the darkened “blast zone” at the landing site toward Glenelg is marked on a HiRISE image (ESP_028335_1755) acquired on 11 August 2012. The locations of pebble conglomerates are marked with red dots.
cemented and made up of rounded to subangular rock fragments larger than 2 mm in diameter in a finer-grained matrix of sand or silt).

Additional evidence for a fluvial interpretation is the stratification at Hottah. Alternating pebble-rich and sand layers (Fig. 3C) indicate fluctuations within sediment transport that result in size sorting of the deposits. In bedload transport, the presence of sand mixed with fine pebbles leads to a sorting instability within flows that produces shallow migrating bedforms (bedload sheets), resulting in fine-scale vertical variations in grain sorting (23), as observed at Hottah.

Alternative sediment transport mechanisms to water flows are inconsistent with the observed rock characteristics. For example, the well-developed rounding of the pebbles together with clast fabric, specifically the grain-to-grain contact and local imbrication, make mass transport as a debris flow unlikely. Likewise, pebble clusters and the relatively wide size range of pebbles within the deposit are inconsistent with transport and deposition by wind. The largest grains mobilized by wind will move via creep driven by impacts from abundant saltating finer grains. On Mars, 1- to 2-mm grains are driven by creep, leading to formation of megaripples observed at both Mars Exploration Rover landing sites [e.g., (24)]. The result of this process is a relatively thin surface layer of uniformly sized clasts due to size-dependent downwind (creep) migration rates, which differs in both geometry and the coarse grain size range (2 to 40 mm) within the martian conglomerates described here. The higher density of liquid fluids relative to air results in higher bed shear stress (and a buoyancy force on the particle), which can mobilize coarse sediment.

A number of factors influence the development of rounded clast perimeters in fluvial transport, including the original clast size, shape, and lithology, as well as the grain size of the bed material (21, 25). Sand commonly acts as an abrasive agent when transported with pebbles in fluvial systems, causing the coarser particles to round more rapidly (21, 22). The presence of coarse sand and rounded pebbles in the martian rocks is consistent with a highly abrasive flow. For clasts of the same size, lithology is the major factor affecting the rate of downstream rounding [e.g., (25–27)]. On the basis of published data for pebbles in natural streams and fluvial abrasion experiments for a range of compositions [e.g., (25–27)], and assuming an initial angular pebble, we estimate a minimum transport distance of a few kilometers to produce a rounded pebble surface. On Mars, the elastic collisions within the flow may have had lower energy due to the reduced gravity, resulting in lower abrasion rates and longer transport distances to achieve similarly rounded pebbles. Overall, the rounded pebbles of apparently diverse lithology within the martian conglomerates are strong evidence for sustained fluvial transport.

The grain size distribution can be used to estimate the critical shear stress for sediment mobility, and in turn the flow depth and mean velocity assuming a water surface slope between 0.1 and 1% (17, 28–30) (tables S3 to S5). This range of slope values corresponds to the nearby alluvial fan slope (1%) and an approximate lower value (0.1%) for gravel-bedded streams [e.g., (31, 32)].
In addition, all Link spectra display a hydrogen peak visible at 656 nm, consistent with the presence of a low proportion of hydrated mineral(s). This peak is present in all points but seems to be higher for the first 25 shots at point 5 (Fig. 6B), corresponding to the Fe-, Ti-, and Cr-bearing component. The depletion of mobile elements (e.g., Na) relative to aluminum in this phase may be consistent with limited alteration. We cannot determine whether the observed hydration is related to in situ aqueous alteration of fine grains, or to minor alteration phases that were already present in the martian crust and transported as fines with the larger clasts. The isolated rock exposures and consistent thickness of beds suggests localized induration after flows ceased.

Overall, the chemical data are consistent with a rock comprising first-cycle clastic sediments with preservation of coarse feldspar grains and minimal alteration products. We conclude that clast size and shape developed predominantly from mechanical rock breakdown by fluvial abrasion, in contrast to terrestrial rivers where the development of weathering rinds is a secondary mechanism contributing to clast diminution and form (e.g., (34)).

**Stratigraphic Interpretation**

The conglomerates have a complex geologic setting: The ancient impact basin they lie within formed approximately 3.6 to 3.8 billion years ago, around the Noachian-Hesperian transition (35, 36), and may have filled completely with sediment before being eroded to the current morphology through aeolian erosion (36). The Bradbury conglomerates are within the crater-fill stratigraphy and document the role of fluvial processes in sedimentation within Gale crater.

Multiple fluvial pathways have been identified at Gale crater from orbital images (e.g., (10)), but none can be connected with confidence to the conglomerates. Both Aeolis Mons and the crater rim show geomorphic evidence for fluvial incision (10, 37) (Fig. 1) and could have been sediment sources for the conglomerates. For example, the conglomerates are located downslope of a large, crater rim–sourced alluvial fan (~80 km²). The transport distances across the alluvial fan (~14 km) and from its drainage basin (~40 km) are consistent with the rounded clast observations. The distal Peace Vallis alluvial fan slope (~1% gradient) can be projected across a topographic depression ~5 km to the conglomerate outcrops. However, there is no evidence to date, except topography, indicating that the Peace Vallis fan extended to this area. In the absence of contact relationships between the Bradbury Rise conglomerates and mapped geomorphic features interpreted as water-formed, the overall stratigraphic context and relative age of the conglomerates are uncertain. Thus, the most parsimonious interpretation is that the conglomerates are distal alluvial fan deposits of unknown age.

Despite the uncertainty in their stratigraphic context, the Bradbury conglomerates constitute a record of past conditions at Gale crater that contrast...
with the modern martian environment, where liquid water is unstable under current atmospheric conditions (35). These ancient fluvial deposits indicate sustained liquid water flows across the landscape—a finding that raises prospects for the former presence of habitable environments on Mars.

References and Notes
6. Rocks at the Pathfinder site with possible sockets and knobs were proposed as candidate conglomerates, but low image quality made this interpretation equivocal.
12. A sol is a martian day.
13. Names have been assigned to areographic features and rocks by the MSL team for planning and operations purposes. These names are not formally recognized by the International Astronomical Union.
14. Cameras on Curiosity's remote sensing mast include four monochrome navigation cameras, each with a 45° field of view (FOV), and two color cameras (Bayer pattern color filter array) that constitute the stereo Mastcam instrument. The left camera has a 34-mm focal length with 15° FOV; the right camera has a 100-mm focal length and 5° FOV. At a distance of 2 m, the Mastcam pixel scales are 440 and 148 μm, respectively. The ChemCam instrument is a package of a Laser-Induced Breakdown Spectrometer (LIBS) coupled to a Remote Micro-Imager (RMI). The full FOV for each RMI is 20 milliradians. The Mars Hand Lens Imager (MAHLI) and Alpha-Proton X-ray Spectrometer (APXS) instruments were not commissioned for tactical operations when the conglomerates were encountered.
17. See supplementary materials on Science Online.
28. Scaling analysis suggests that Mars’ lower gravity has only a minor effect on fluvial gradients at the threshold of motion and bedform configuration. Therefore, it is appropriate to compare terrestrial fluvial bedforms and gradients to their martian counterparts.
35. The Noachian is a geologic system on Mars representing the oldest period of the planet’s geologic history, characterized by high impact rates.

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Supplementary Materials
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Methods
Supplementary Text
Figs. 51 to 53
Tables S1 to S6
References (42–56)
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