

Special Collection:

Aeolian-Fluvial Interactions
across the Solar System

Key Points:

- We identify ten decameter-wide concave-up scour-and-fill structures within aeolian strata of Aeolis Mons, Gale crater
- Most scour structures have symmetric cross-sectional profiles filled with draping, planar-laminated facies interpreted as aeolian deposits
- The scour architectures are consistent with aeolian blowout structures suggesting a period of higher-intensity wind conditions

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. L. Roberts,
a.roberts21@imperial.ac.uk

Citation:

Roberts, A. L., Gupta, S., Banham, S. G., Cowart, A., Edgar, L. A., Rapin, W., et al. (2025). Paleo-scours within the layered sulfate-bearing unit at Gale Crater, Mars: Evidence for intense wind erosion. *Journal of Geophysical Research: Planets*, 130, e2024JE008680. <https://doi.org/10.1029/2024JE008680>

Received 19 AUG 2024

Accepted 26 FEB 2025

Author Contributions:

Conceptualization: Amelie L. Roberts, Sanjeev Gupta, Steven G. Banham, Aster Cowart, Lauren A. Edgar, William Rapin, William E. Dietrich,

© 2025 Triad National Security, LLC. Jet Propulsion Laboratory, California Institute of Technology and The Author(s). Government sponsorship acknowledged. This article has been contributed to by U.S. Government employees and their work is in the public domain in the USA. This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Paleo-Scours Within the Layered Sulfate-Bearing Unit at Gale Crater, Mars: Evidence for Intense Wind Erosion

Amelie L. Roberts¹ , Sanjeev Gupta¹, Steven G. Banham¹ , Aster Cowart², Lauren A. Edgar³, William Rapin⁴, William E. Dietrich⁵, Joel M. Davis¹ , Edwin S. Kite⁶ , Gwénaél Caravaca⁴ , Claire A. Mondro⁷ , Patrick J. Gasda⁸ , Jeffrey R. Johnson⁹ , Stéphane Le Mouélic¹⁰ , Deirdra M. Fey¹¹ , Alexander B. Bryk⁵ , Gerhard Paar¹² , Emma R. A. Harris^{1,13} , Abigail Fraeman¹⁴ , and Ashwin R. Vasavada¹⁴ 

¹Department of Earth Science & Engineering, Imperial College London, London, UK, ²Planetary Science Institute, Tucson, AZ, USA, ³Astrogeology Science Center, U.S. Geological Survey, Flagstaff, AZ, USA, ⁴Institut de Recherche en Astrophysique et Planétologie (IRAP), UMR 5277, Université Paul Sabatier Toulouse III, CNRS, CNES, Toulouse, France, ⁵Department of Earth & Planetary Science, University of California, Berkeley, California, USA, ⁶Department of Geophysical Sciences, University of Chicago, Chicago, IL, USA, ⁷Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA, ⁸Los Alamos National Laboratory, Los Alamos, NM, USA, ⁹John Hopkins University Applied Physics Laboratory, Laurel, MD, USA, ¹⁰Laboratoire de Planétologie et Géosciences, CNRS UMR 6112, Nantes Université, University Angers, Le Mans Université, Nantes, France, ¹¹Malin Space Science Systems, San Diego, CA, USA, ¹²JOANNEUM RESEARCH Institute for Information- and Communication Technology, Graz, Austria, ¹³Department of Earth Sciences, Natural History Museum, London, UK, ¹⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

Abstract The surface of modern Mars is largely shaped by wind, but the influence of past wind activity is less well constrained. Sedimentary rocks exposed in the lower foothills of Aeolis Mons, the central mound within Gale crater, record a transition from predominantly lacustrine deposition in the Murray formation to aeolian deposition in the Mirador formation. Here, we report a series of enigmatic decameter-wide, concave-up scour-and-fill structures within the Mirador formation and discuss their formation mechanisms. Using panoramic images of stratigraphy exposed in cliff faces acquired by the *Curiosity* rover, we map the extent, distribution and orientation of the scour-and-fill structures and document the sedimentary facies within and surrounding these structures. The scours are grouped into two classes: (A) scours with a simple, symmetric morphology and light-toned, draping infill; and (B) scours with lateral pinching and dark-toned infill. We find that the scour-enclosing environment is composed of planar, even-in-thickness laminations with a pin-stripe pattern which we interpret as wind-ripple strata formed within an aeolian sandsheet environment. Class B contains cm-scale cross-bedding and a wing-shaped feature making this scour-and-fill structure consistent with fluvial processes. We interpret scour fill of class A as an aeolian infill due to similarities with the surrounding sandsheet strata. The broad morphologies and distribution of class A are also consistent with the geometry of blowout structures formed by localized, enhanced wind deflation. These paleo-blowout structures occur clustered within the same stratigraphic interval, which may imply that they record an interval of intensified wind activity at Gale crater.

Plain Language Summary Sedimentary rocks on Mars record clues to ancient environments and the processes that shape landscapes on the planet. The *Curiosity* rover has been exploring sedimentary rocks displaying a shift from formation in an ancient lake environment to a sand dune desert environment in Gale crater. This transition has been hypothesized to record a change in ancient climate. Here we reconstruct past surface processes as recorded in wind-blown strata using observations from the Mastcam cameras onboard *Curiosity*. We show that these strata are segmented by a series of tens-of-meters wide, erosional surfaces visible in cliff faces. As the surrounding rocks are formed of thin layers that resemble sand deposits formed by wind ripples when they migrate in a desert environment, the erosional surfaces must have been infilled by wind-blown sand. The geometry of the erosional surfaces is inconsistent with erosion by water but instead is consistent with wind-blown processes. We suggest that these surfaces likely formed by localized wind erosion in desert environments: features called “blowouts.” As blowouts often form under strong wind conditions and these surfaces are clustered at similar elevations and associated rock units, these features may indicate a transition to a period of strong, sustained wind in Gale crater.

Edwin S. Kite, Alexander B. Bryk, Abigail Fraeman, Ashwin R. Vasavada
Data curation: Amelie L. Roberts, Patrick J. Gasda, Jeffrey R. Johnson, Stéphane Le Mouélic, Deirdra M. Fey, Gerhard Paar, Abigail Fraeman, Ashwin R. Vasavada
Formal analysis: Amelie L. Roberts, Sanjeev Gupta
Investigation: Amelie L. Roberts, Sanjeev Gupta, Steven G. Banham, Aster Cowart, Lauren A. Edgar, William Rapin, William E. Dietrich, Edwin S. Kite, Claire A. Mondro, Alexander B. Bryk, Abigail Fraeman, Ashwin R. Vasavada
Methodology: Amelie L. Roberts, Sanjeev Gupta
Project administration: Abigail Fraeman, Ashwin R. Vasavada
Resources: Amelie L. Roberts, Sanjeev Gupta, Steven G. Banham, Joel M. Davis, Patrick J. Gasda, Jeffrey R. Johnson, Stéphane Le Mouélic, Deirdra M. Fey, Gerhard Paar, Abigail Fraeman, Ashwin R. Vasavada
Software: Amelie L. Roberts, Deirdra M. Fey, Gerhard Paar
Supervision: Sanjeev Gupta, Steven G. Banham, Joel M. Davis
Validation: Amelie L. Roberts
Visualization: Amelie L. Roberts, Abigail Fraeman
Writing – original draft: Amelie L. Roberts
Writing – review & editing: Amelie L. Roberts, Sanjeev Gupta, Steven G. Banham, Aster Cowart, Joel M. Davis, Edwin S. Kite, Gwénaél Caravaca, Claire A. Mondro, Patrick J. Gasda, Jeffrey R. Johnson, Stéphane Le Mouélic, Emma R. A. Harris, Ashwin R. Vasavada

1. Introduction

Large-scale erosional scour structures preserved in the stratigraphic record are important signatures of landscape evolution on ancient planetary surfaces. Such surfaces can be formed by erosion and entrainment of sediment by both aqueous (Gibling, 2006; Priddy & Clarke, 2020) and aeolian processes (e.g., Blakey, 1988; Rubin & Hunter, 1982). Aeolian erosional structures may arise by autogenic processes such as scour pit migration during dune advancement (e.g., Cardenas et al., 2019; Kocurek & Day, 2018; Rubin & Hunter, 1982) or by allogenic processes such as base-level fall, changes in magnitude of sediment-transporting winds, changing sediment availability, and the position of the water table (Havholm & Kocurek, 1994; Kocurek & Day, 2018; Kocurek et al., 2001). Analysis of the geometry and distribution of ancient scour bedforms permits insight into past environmental evolution.

In this paper, we investigate a series of decameters-wide scour-and-fill structures preserved in the Chenapau member of the Mirador formation which forms part of the stratigraphy of Aeolis Mons (informally Mount Sharp), Gale crater, Mars. Aeolis Mons is a ~5.5 km tall mound of layered sedimentary rocks that is interpreted to be a remnant of extensive crater-filling strata that formerly extended across the entire crater (e.g., R. Anderson & Bell, 2010; Grant et al., 2014; Grotzinger et al., 2015; Thomson et al., 2011). Since 2012, the *Curiosity* rover has been characterising changing surface paleoenvironments in Gale crater through interrogation of this stratigraphic succession. The scour-and-fill structures that are the focus of this work occur within the Mirador formation and within a section interpreted to have formed in an aeolian sandsheet environment (Edgar et al., 2024; Roberts et al., 2023). Scour-and-fill structures can form through either aqueous or aeolian processes, and thus may represent processes operating within the prevailing aeolian conditions, or brief returns to fluvio-lacustrine depositional conditions present within the lowermost strata observed along *Curiosity's* traverse (Grotzinger et al., 2014, 2015; Williams et al., 2013). The nature of the erosional and depositional processes that created and infilled scours can provide insight into the climate of the region at the time of their formation such as wind conditions and the availability of surface water and sediment. Consequently, robust characterization and interpretation of their origin is required to understand the evolution of the Gale crater paleoenvironment ~3.6 billion years ago, a period that has been inferred to represent an important global climate change (e.g., Bibring et al., 2006; Carr & Head, 2010; Ramirez & Craddock, 2018). To address this, we conducted an analysis of the morphology and sedimentary character of these scour-and-fill structures to understand their formative processes and paleoenvironments.

The main objectives of this paper are to: (a) describe the geometries of these decameter-wide erosional scours and their sedimentary infill, (b) describe the sedimentary character of the scour-and-fill structures and the host strata, (c) evaluate the mechanisms and possible controls on scour formation, and (d) discuss the implications for landscape evolution at Gale crater.

2. Geologic and Stratigraphic Context

Gale crater (Figure 1a) is a ~155 km-wide impact crater. It is located 5° south of the Martian equator, near the dichotomy boundary between the heavily cratered southern highlands and the relatively smooth northern lowlands (Tanaka et al., 2014). The crater has been dated to approximately 3.7–3.8 billion years (Ga) from crater counting of the impact ejecta blanket (e.g., Le Deit et al., 2013; Thomson et al., 2011) and subsequently infilled by sedimentary deposits over a 200–500 million year (Myr) period after crater formation (e.g., Grant et al., 2014; Thomson et al., 2011), including many periods of aeolian erosion (Dromart et al., 2021). The infilling material in Gale crater was later exhumed by predominantly aeolian processes (W. Anderson & Day, 2017; Day & Kocurek, 2016; Grotzinger et al., 2015; Kite et al., 2013; Malin & Edgett, 2000) leaving a ~5.5 km tall central mound—Aeolis Mons (informally Mount Sharp)—exposing layered stratigraphy (R. Anderson & Bell, 2010; Malin & Edgett, 2000) (Figure 1a). Orbital spectral observations of the north face of Aeolis Mons identified a vertical succession from clay-bearing strata transitioning to layered sulfate-bearing strata, which are unconformably overlain by anhydrous mineral-bearing strata (Figure 1b; Fraeman et al., 2016; Milliken et al., 2014). This clay-to-sulfate transition is found to be a variable and inconsistent transition, with discontinuous inclusions of clay-bearing strata amongst the layered sulfate-bearing strata from further orbital studies (Sheppard et al., 2021).

As of middle 2024, *Curiosity* has traversed over 800 vertical meters of stratigraphy since landing at Gale in August of 2012 (Figure 2), documenting three major stratigraphic groups at the time of writing: the Bradbury,

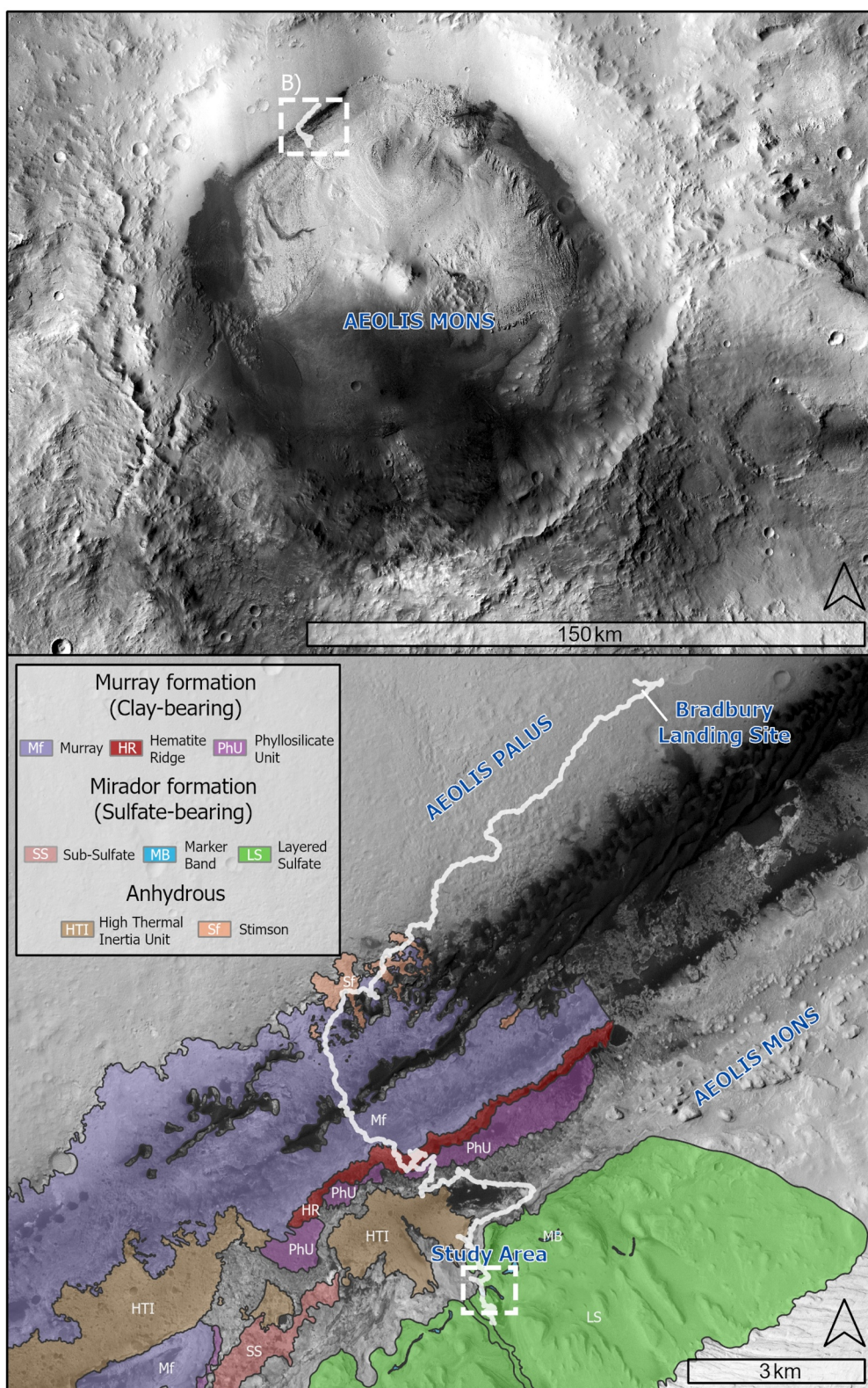


Figure 1.

Mount Sharp, and Siccar Point groups. The Bradbury group consists of fluvial sandstones and conglomerates (Williams et al., 2013) which outcrop on the plains between the crater rim and the base of the mound (Aeolis Palus) and are inferred to interfinger with strata of the Mount Sharp group, which form the sedimentary rocks in lower Aeolis Mons (Grotzinger et al., 2015). The Mount Sharp group consists of stratigraphy which bears hydrated minerals identified from orbit prior to landing (e.g., Milliken et al., 2010). These groups are unconformably overlain by the Siccar Point group. The Stimson formation is the only unit of the Siccar Point group identified so far (Banham et al., 2022; Watkins et al., 2022), and is composed of large-scale aeolian cross-bedded units (Banham et al., 2018) although minor soft sediment deformation structures show that near-surface fluid was present before lithification (Banham, Roberts, et al., 2024).

The Mount Sharp group, currently documented as approximately 700 m thick at the time of writing, is subdivided into three formations (Figure 2). Exposed at the base of the mound is the Murray formation which comprises clay-bearing strata with lacustrine mudstones and subordinate aeolian and fluvial sandstones (Edgar et al., 2020; Grotzinger et al., 2014; Rivera-Hernández et al., 2019; Stack et al., 2019). It is conformably overlain by the Carolyn Shoemaker formation which contains interbedded mudstones and cross-bedded sandstones interpreted as an intermittent fluvial and lacustrine environment (Caravaca, Mangold, et al., 2022; Cardenas et al., 2022; Fedo et al., 2022; Gwizd et al., 2024). Overlying the Carolyn Shoemaker formation, the Mirador formation is comprised of the layered sulfate-bearing strata seen from orbit (Fraeman et al., 2016).

The Mirador formation is subdivided into a series of members (Figure 2). The members which comprise the base of the Mirador formation contain large sets of cross-stratification which are attributed to the migration of aeolian dunes (Rapin et al., 2021). These meter-scale cross-sets occur throughout the Dunnideer, Port Logan, and Contigo members of the Mirador formation with varying degrees of diagenetic alteration (Edgar et al., 2024; Rapin et al., 2023). Within the Contigo member, there is evidence for intermittent lacustrine and fluvial deposition through meter-scale resistant lenses (Caravaca, Le Mouelic, et al., 2022; Gupta, Dietrich, Lewis, Kite, et al., 2023). This is overlain by the Catrimani member which exhibits planar, laterally extensive laminae interpreted to be from the migration of wind ripples in aeolian sandsheets (Edgar et al., 2024; Roberts et al., 2023). Sharply overlying the Catrimani member is a thin (~0.5 m thick) member called the Amapari member (e.g., Mondro et al., 2025; Thompson et al., 2024). This member is dark-toned, distinctive and can be seen from orbit as a marker band used in geomorphic mapping attempts (R. Anderson & Bell, 2010; Milliken et al., 2010; Thompson et al., 2024; Thomson et al., 2011; Weitz et al., 2022). This member contains symmetrical ripples interpreted to be formed in a shallow lake (Gupta, Dietrich, Lewis, Mondro, et al., 2023; Weitz et al., 2023). The Amapari member is overlain by the Chenapau member which consists of planar-parallel strata which are interstratified with the large-scale scour-and-fill structures reported here.

3. Data and Methods

3.1. Instruments

The architecture of the scours primarily was investigated using the Mastcam, Navcam and ChemCam instruments aboard the *Curiosity* rover.

The two Mast Cameras (Mastcams—left and right; Bell et al., 2017; Malin et al., 2017), are located at the top of the rover's remote sensing mast (RSM)—~1.9 m above ground level—and provide high-resolution color and stereo photomosaics. The cameras are separated by ~24.2 cm which allows for stereo data collection at the spatial sampling of the M34 camera, which is 0.22 mrad/pixel (~0.45 mm/pixel at 2 m viewing distance). The 0.074 mrad/pixel sampling of the M100 camera provides ~0.15 mm/pixel at 2 m viewing distance. Mastcam data products were processed (Data Set S1) and mosaicked to optimize both visibility and accuracy of the sedimentary

Figure 1. Study location at Gale crater. (a) Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) mosaic (~5 m per pixel resolution; Dickson et al., 2018) showing Gale crater and Aeolis Mons. White dashed box shows *Curiosity's* exploration extent. (b) CTX mosaic overlain by a digital terrain model (DTM) hillshade and ~20 m contour intervals derived from Mars Orbital Laser Altimeter (MOLA) and High Resolution Imaging Science Experiment (HiRISE) data (~1 m per pixel resolution; Calef & Parker, 2016; Smith et al., 2001), shows the regional extent *Curiosity's* traverse within Gale crater until Sol 3749. Major Mount Sharp orbital units modified from Fraeman et al. (2016) on the northern flank of Aeolis Mons are displayed for context. White dashed box shows the study area at the base of the layered sulfate unit within Marker Band valley (Sols 3576–3749). Image credit: NASA/JPL/MSSS/The Murray Lab.

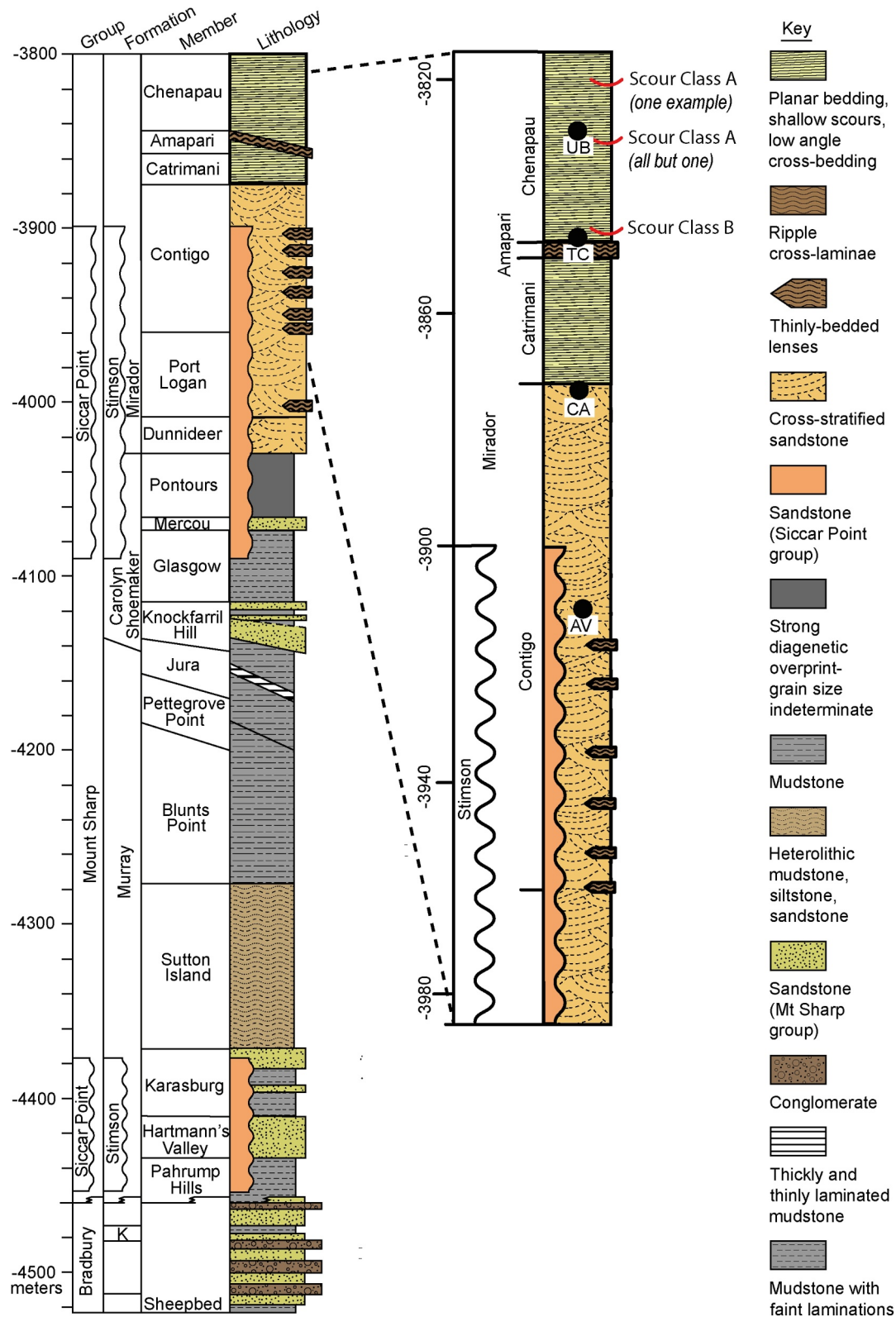


Figure 2. Stratigraphic column modified from the Mars Science Laboratory (MSL) Team's Sedimentology and Stratigraphy Working Group displays the vertical extents of the Bradbury, Mount Sharp and Siccar Point groups as encountered along the rover traverse. The inset stratigraphic column illustrates the vertical extents of the Contigo, Catrimani, Amapari, and Chenapau members of the Mirador formation, providing the stratigraphic context for the scour-and-fill structures in Marker Band valley. These structures are highlighted in red. Drill holes AV—Avanavero, CA—Canaima, TC—Tapo Caparo, and UB—Ubjara are also shown for reference.

architecture for analysis. Mastcam spatial sampling of scour image coverage ranged from 17 to 5.8 mm/pixel depending on the image range (Table S4 in Supporting Information S1).

The Navigation cameras (Navcams; Maki, 2018; Maki et al., 2012) are also located near the top of the RSM and provide 360°, monochromatic (greyscale) context stereo mosaics at every rover waypoint providing additional spatial context for Mastcam mosaics. The left and right navigation cameras both have a fixed focal length of 14.67 mm and provide 0.82 mrad/pixel. With an interocular length of ~42.4 cm, stereo three-dimensional mesh products were derived (Alexander et al., 2006) typically accurate to a distance of ~30–50 m from the rover and provided three-dimensional data for scours within range.

ChemCam (Wiens et al., 2012) has the capability to take long distance (LD), high-resolution, monochromatic image mosaics with the Remote Micro-Imager (LD RMIs; Le Mouélic et al., 2015, 2019). With a narrow field of view at a fixed focal length of ~700 mm and 0.0205 mrad/pixel, LD RMIs were sometimes used to supplement Mastcam data where instrument pointing safety restrictions allowed.

The Mars Hands Lens Imager (MAHLI) is attached to the turret on *Curiosity's* arm, and can provide detailed color images with spatial sampling up to ~14 μm per pixel (Edgett et al., 2012). Typical MAHLI imaging procedures involve a suite of images captured at nominal toolframe distances of 1 cm (spatial sampling of 16–21 μm per pixel), 5 cm (spatial sampling 31 μm per pixel), and 25 cm (spatial sampling of 100 μm per pixel) (Yingst et al., 2016). A second observation suite, referred to as a “dog's eye,” places MAHLI orthogonal to the sedimentary structure within the outcrop. Therefore, MAHLI can be used to resolve fine-scale sedimentary structures and textures at a hand-lens scale with the ability to typically resolve grain sizes of coarse silt, ~62.5 μm , or larger (Edgett et al., 2015; Yingst et al., 2016).

The rover-derived data products were supplemented with ~25 cm/pixel orbital images from the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007). For three-dimensional data, a ~1 m/pixel Digital Terrain Model (DTM) generated from HiRISE stereo pairs and registered to the Mars Orbiter Laser Altimeter data products (Calef & Parker, 2016; D. E. Smith et al., 2001) was used. These data products aided in photogeological mapping, rover and outcrop localization, and strategic planning of rover data collection sites (Figure S1 in Supporting Information S1).

3.2. Data Collection and Imaging Strategy

Between Sols 3576 and 3749 (the number of Martian days since *Curiosity* landed in Gale Crater), the rover traversed across Marker Band valley. This valley is topographically defined by the buttes Orinoco, Chenapau, and Bela Vista, as well as a ledge forming the western valley flank, all of which host nine of the scours described in this manuscript (Figures 3 and 4). Additionally, another scour was identified during a rover detour up to Gediz Vallis Ridge from this valley. When time, data volume, and energy constraints allowed (e.g., Vasavada, 2022), mosaics were planned around the rover's closest approach along the Mount Sharp Ascent Route (MSAR) and when viewsheds were orthogonal to the feature of interest to avoid distortion from image foreshortening effects. Seven key M34 and M100 stereo mosaics of the scour-and-fill structures were taken (Figure S1 and Table S1 in Supporting Information S1). Due to lighting and instrument safety constraints, only two LD RMIs were taken of these scours (Table S2 in Supporting Information S1). All outcrops, geologic units, and rock targets investigated by *Curiosity* are informally named by the MSL team based on naming conventions detailed in Vasavada et al. (2014).

Although the rover traverse did not intersect any scour-and-fill structures, the traverse crossed laterally equivalent strata in two separate traverse sections—along the Canta detour and again along the main traverse route west of Chenapau (Figure 3)—which provided nearfield (<10 m distance) observations of the strata to enable reconstruction of depositional processes. The scour-hosting facies were characterized by a transition from relatively “dark-toned” and “light-toned” strata (Figure 4d). These stratigraphic transitions were correlated and mapped around the two scour-hosting buttes and onto the projected rover traverse (Roberts et al., 2023). This map of the stratigraphic contact (Figure S2 in Supporting Information S1) was then used to visit the lateral equivalent of the scour-hosting facies with the rover for on-ground analysis.

3.3. Data Analysis

As the range to various sections of the scours varied relative to the rover (Figure S1 and Table S4 in Supporting Information S1), different approaches were required to quantitatively assess the scours. The three-dimensional

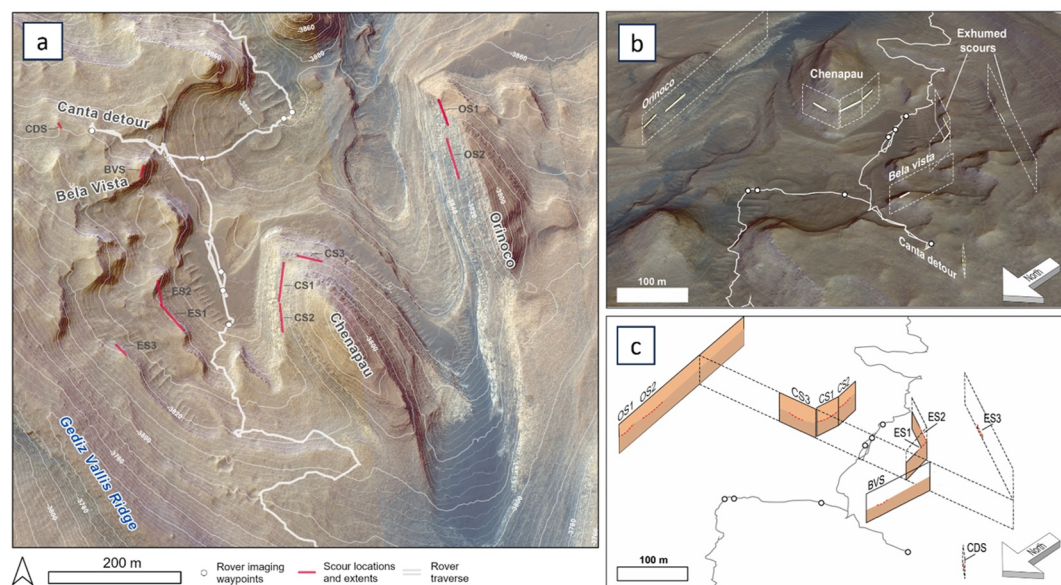


Figure 3. Context of scour-and-fill structures. (a) High Resolution Imaging Science Experiment (HiRISE) mosaic (~25 cm per pixel; Calef & Parker, 2016) overlain by a MOLA and HiRISE derived digital terrain model hillshade shows the Marker Band valley region of the rover traverse (from Sols 3576 to 3749). Red lines show scour locations, orientations, and extents with shorthand labels (longhand names can be found in Table 1). White line shows *Curiosity*'s traverse. Black-rimmed circles show the key imaging locations. (b) ArcGIS Pro HiRISE scene-view of the location, extent, and orientations (see Table 1 for numeric orientations) of the scour-and-fill structure mosaics included in this paper (dashed white lines). Thick white lines delineate the scours. (c) Fence diagram that shows the scour-and-fill structure outcrop orientations, extents, and locations with shorthand labels. Red dashed lines delineate the scours, gray line delineates the rover's traverse, black-rimmed white circles show key imaging locations, and the dark/light-toned shading shows the dark- and light-toned unit contact boundary. Image credits: NASA/JPL/University of Arizona.

Navcam mesh (Alexander et al., 2006) was used to provide width and thickness data of the scours at distances less than ~50 m. At distances further than 50 m, the scours were mapped using *ArcGIS Pro 3.1.0* onto the HiRISE orthomosaic and used as a base to correlate features of interest visible in both the HiRISE and Mastcam mosaics (Table S4 in Supporting Information S1). This was supplemented with GIS projected viewsheds using the HiRISE DTM based on the rover co-ordinates and imaging specifications. The mapped scours could then be quantitatively assessed using the HiRISE DTM. To account for foreshortening when measuring apparent dips, we only measured the parts of the image mosaic oblique to the scours (Figure S1 in Supporting Information S1).

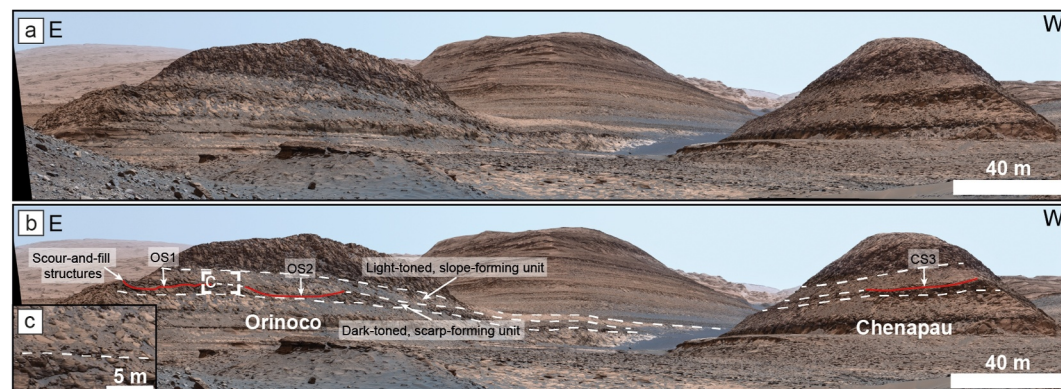


Figure 4. (a) Overview mosaic showing Orinoco and Chenapau buttes in the Marker Band valley study area (Mastcam mosaic MR_mc102554, acquired on Sol 3562, at Sol 3650 end-of-drive location). (b) Interpreted image showing the scour-enclosing unit boundaries (dashed white lines) and the scour-and-fill structures (red lines). (c) Detail showing the stratigraphic context of the dark- and light-toned units. Image credits: NASA/JPL-Caltech/MSSS.

Analysis of the host stratigraphy was predominantly performed using stereo coverage derived from M34 and M100 data products and more detailed coverage from M100. MAHLI images help resolve fine-scale sedimentary structures in the host stratigraphy for a more detailed facies characterization. Measurements of laminae thickness could be measured based on visual inspection of MAHLI images orthogonal to bedding as described by Edgar et al. (2020), using the open-source image processing program, ImageJ (Schneider et al., 2012).

4. Stratigraphic Context of Scour-and-Fill Structures

Within the Chenapau member (Figure 2), ten decameter-wide scour surfaces were identified truncating low-angle, planar strata. These scours occur in association with three visually defined stratigraphic units within the Chenapau member. Most scours are incised into a dark-toned unit and are overlain by a light-toned unit (Figures 3 and 4). The remaining scours are embedded within a light-toned unit where diagenetic overprinting has obscured the sedimentary textures of the host stratigraphy. Hereafter, this will be referred to as the “diagenetically overprinted unit.” Here, we provide a brief description of these units from both the outcrop scale (50–300 m range) and rover nearfield scale (<10 m range) and present our interpretation of their depositional setting.

4.1. Observations

4.1.1. Dark-Toned Stratigraphic Unit

A series of scours incise a ~6 m thick interval of visually dark-toned, scarp-forming strata at a single stratigraphic level between elevations –3,833 and –3,828 m. At an outcrop scale, this interval is found to be comprised of cm-scale sets of recessive-resistant packages of planar strata (Figure 4c). The dark-toned stratigraphic interval was encountered along the rover's traverse from Sols 3801 to 3817, between elevations –3,832 and –3,826 m (Figure S2 in Supporting Information S1). Nearfield imaging shows 1–8 cm thick recessive planar packages comprised of planar, laterally extensive laminae that are <1 mm thick and which can be traced across blocks for over ~3 m. Planar, weathering-resistant laminae separate these recessive sets and protrude out from bedrock targets (Figure 5a). Isolated sets of indurated laminae ~1 cm thick are observed within this unit.

4.1.2. Light-Toned Stratigraphic Unit

Overlying both the dark-toned stratigraphic interval and the scours is a light-toned interval measuring ~8 m thick. Along section, this interval appears predominantly structureless although some sections show evidence of planar stratification (Figure 4). The light-toned stratigraphic interval was encountered along the rover's traverse from Sols 3812 to 3867, between elevations –3,826 and –3,814 m (Figure S2 in Supporting Information S1). Nearfield observations show the interval is composed of planar and laterally extensive laminae (Figures 5b and 5d). Individual laminae—traced laterally for ~3 m across outcrops—demonstrate planar geometry with no thickness variation. Each individual lamina is composed of a light-toned/resistant and dark-toned/less resistant component resembling a pin-stripe pattern (Figure 5d). Measured sections of this stratigraphic interval in MAHLI images show remarkably even-in-thickness laminae, with an apparent thickness of ~0.76 mm and a standard deviation of 0.058 mm (Figure S3 in Supporting Information S1). No other sedimentary structures were identified from rover observations.

4.1.3. Diagenetically Overprinted Unit

Along the “Canta detour” (Figure 3), the original sedimentary structures and textures are difficult to resolve. The rocks are heavily weathered and often have a nodular surface texture with cross-cutting veins (Figure 5c) which we interpret to be from diagenetic overprinting.

4.2. Interpretation

The uniformity, lateral persistence, and planar nature of the laminae comprising the light-toned strata resemble laminae formed by the migration of wind ripples on Earth (e.g., Ferronatto et al., 2019; Kocurek & Nielson, 1986) and Mars (Banham et al., 2018). On Earth, wind ripples are often identified by inverse grading, where fines and silts are sequestered in ripple troughs and protected from migration of the coarser grained ripple-component (Fryberger & Schenk, 1988; Mountney, 2006a). Inverse grading is often difficult to identify on Mars as the finer particles are smaller than image resolution limits (e.g., Banham et al., 2022; Stack et al., 2019). However, a thin

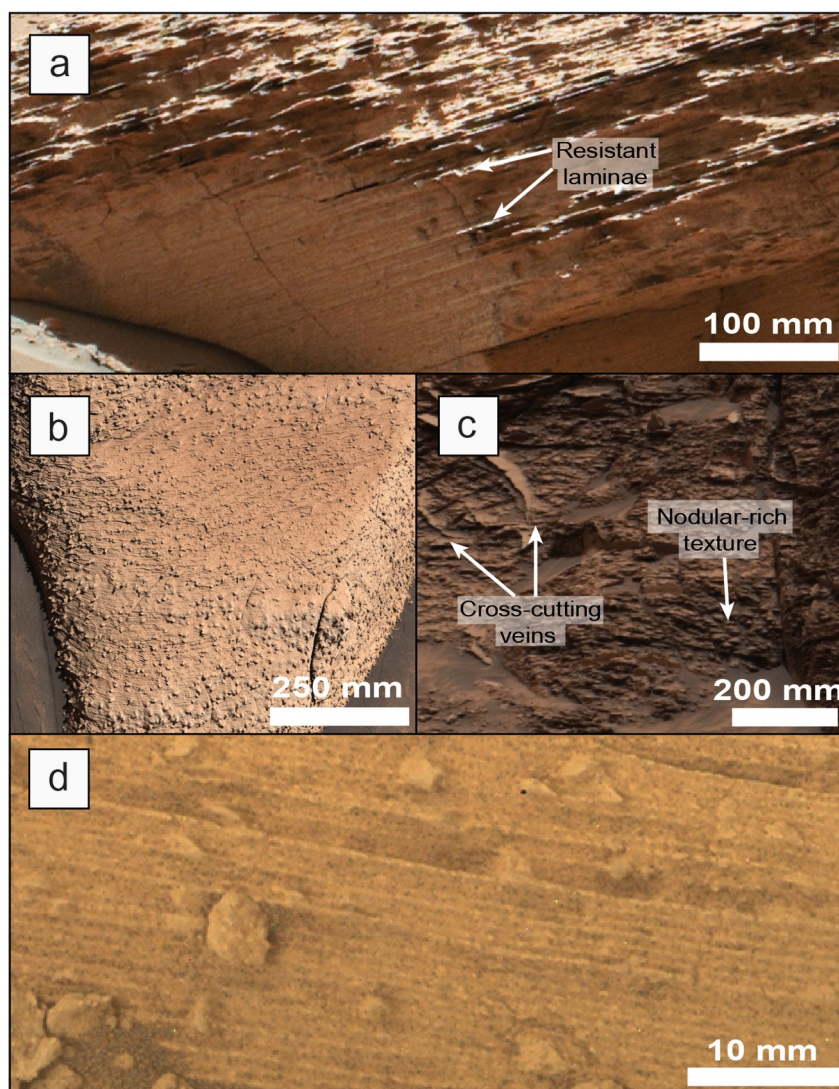


Figure 5. Examples of selected facies characteristic of the scour-enclosing strata. (a) Mastcam photomosaic of the dark-toned unit with resistant laminae separating cm-scale thick sets of light-toned, recessive laminae (Mastcam mosaic MR_mcaml03951, acquired on Sol 3807, at Sol 3805 end-of-drive location). (b) Mastcam mosaic of the light-toned unit (Mastcam mosaic MR_mcaml04131, acquired on Sol 3845, at Sol 3843 end-of-drive location). (c) Mastcam mosaic of the diagenetically overprinted unit with a nodular-rich texture and cross-cutting veins (Mastcam mosaic MR_mcaml03061, acquired on Sol 3648, at Sol 3646 end-of-drive location). (d) Part of a MAHLI dogs eye mosaic of the light-toned unit showing the laterally extensive, light-toned, planar laminae (Kastria Spring target, 25 cm stand off). Image credits: NASA/JPL-Caltech/MSSS.

layer of fine particles often has a distinct tone (Mountney, 2006a) or exhibits preferential cementation (Fryberger & Schenk, 1988) compared to the rest of the lamina, creating a distinct pin-stripe pattern characteristic of aeolian wind-ripples (Fryberger & Schenk, 1988; Mountney, 2006a). Our observations of this pattern within the light-toned stratigraphic interval suggest the strata originated from wind-ripple migration (Figure 5). Furthermore, laminae formed by wind-ripple migration can be evenly laminated and have similar thicknesses (e.g., Banham et al., 2018; Fryberger & Schenk, 1988; Fryberger et al., 1979; Hunter, 1977), like those identified in the light-toned unit (Figures 5b and 5d). The low-angle, flat depositional habit of the laminae and their lateral continuity over ~2 m lead us to interpret these deposits as products of wind-ripple migration in an aeolian sandsheet environment: a flat, arid environment covered in wind-blown sand (e.g., Chakraborty & Chakraborty, 2001; Ferronatto et al., 2019; Grotzinger et al., 2005; Kocurek & Nielson, 1986). The absence of dune cross-

Table 1

Detailed Measurements of the Elevations, Apparent Scour-and-Fill Structure Widths, Apparent Scour Thicknesses, and Apparent Dips of Scour Margins for Scours in Classes A and B

Class	Scour	Apparent width (m)	Apparent thickness (m)	Elevation (m)	Apparent dip of scour margin relative to underlying strata	Cross-section azimuth
A	Chenapau Scour One (CS1)	~61	~4	−3,832 to −3,836	~14–16°	8°
	Chenapau Scour Two (CS2)	~41	~3	−3,834 to −3,829	~16–18°	355°
	Orinoco Scour Two (OS2)	~62	~4	~−3,828 to ~−3,836	~8–10°	343°
	Chenapau Scour Three (CS3)	~37	~2	~−3,832 to ~−3,834	<14°	103°
	Orinoco Scour One (OS1)	~40	~3	~−3,832 to ~−3,838	Section 1: <21°, Section 2: <11°	340°
		~Part 1 = ~21				
		~part 2 = ~12				
		~part 3 = ~4				
	Bela Vista Scour (BVS)	~16 ^a	~<1 ^a	~−3,842 to −3,843	Unidentifiable	199°
	Exhumed Scour One (ES1)	~40 ^a	~1 ^a	~−3,838 to −3,839	12–13°	140°
B	Exhumed Scour Two (ES2)	~49 ^a	~3 ^a	~−3,838 to −3,841	<16°	148°
	Exhumed Scour Three (ES3)	~19 ^a	~4 ^a	~−3,819 to −3,823	Unidentifiable	134°
	Canta Detour Scour (CDS)	~7	~<0.5	~−3,850	Unidentifiable	150°

^aPartially preserved.

stratification may indicate a process inhibiting dune development such as the presence of near-surface water (e.g., Kocurek & Nielson, 1986), or a small degree of cementation by salt (Nickling, 1984).

We interpret that the apparently dark-toned appearing strata were similarly deposited in an aeolian environment due to the recessive sets of planar, even-in-thickness, and laterally extensive laminae. The prominent laminae are interpreted to be more indurated than the light-toned recessive sets, providing additional weathering resistance. This induration is attributed to processes post-dating scour formation such as early cementation due to varying fluid retention properties, the presence of fine-grained clays trapped in the inverse graded wind-ripple laminae (Cain & Mountney, 2009), or post-depositional diagenesis due to variations in permeability influencing fluid flow. In aeolian rocks, these properties are thought to be influenced by changes in grain size, grain packing, wrought by variations in sediment transport process (e.g., Chandler et al., 1989; Fryberger & Schenk, 1988; Prosser & Maskall, 1993; Taggart et al., 2010). The presence of resistant laminae is interpreted as the cause of the darker tone of this unit at outcrop scale due to centimeter-scale self-shadowing. Both the dark-toned and light-toned strata are interpreted as aeolian facies suggesting an overall aeolian setting within which the scours formed.

5. Description of Scours-and-Fill Structures

Here, we describe ten scour-and-fill structures identified within the Chenapau member of the Mirador formation. We broadly divide these structures into two classes A and B based on both morphology and infill characteristics. Class A consists of nine large scour-and-fill structures with a simple, symmetric morphology and light-toned draping infill. Class B consists of one smaller scour-and-fill structure with a dark-toned infill and winged-shape feature. Within class A, the nine scour-and-fill structures exhibit slight variations in their morphology and infill architecture. Five scour-and-fill structures have a simple, symmetric morphology and light-toned infill; two scour-and-fill structures have a complex scour and infill architecture; and three scour-and-fill structures are heavily exhumed, preserving little to no infill. Four structures preserve their complete geometry and infill architecture and the remaining six structures are partially preserved (Table 1). The locations of these scours are shown in Figure 3. The geometry and infill stratigraphy of each of these scour-and-fill structures are described below.

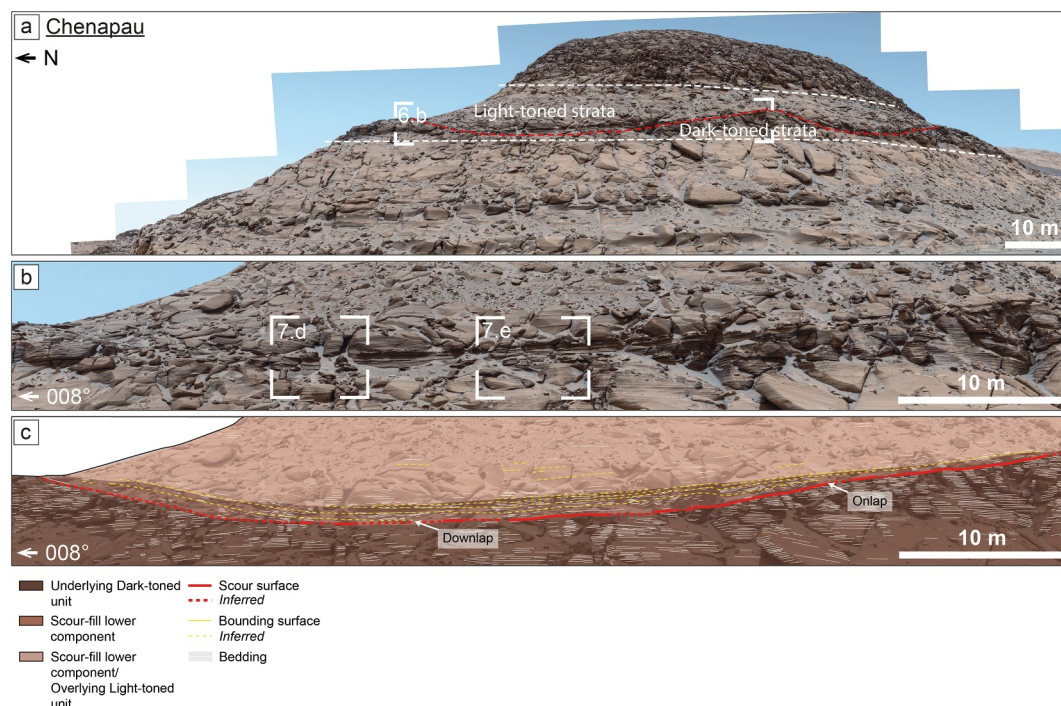


Figure 6. Chenapau butte mosaic showing Chenapau Scour 1 (CS1). (a) Mastcam mosaic of CS1 illustrating stratigraphic contacts (white dashed lines) and locations of erosive bases to scour-and-fill structures (red dashed lines) (Mastcam mosaic MR_mcam103485 acquired on Sol 3727, at Sol 3724 end-of-drive location). (b) Detail of CS1 uninterpreted. (c) Interpretation of CS1 showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. Image credits: NASA/JPL-Caltech/MSSS.

5.1. Class A Scour-and-Fill Structures With a Simple, Symmetric Morphology and Light-Toned Infill

5.1.1. Observations

5.1.1.1. Chenapau Scour 1 (CS1)

CS1 is present on the north side of the western face of Chenapau butte and exhibits a cross-sectional profile measuring ~ 60 m wide and ~ 4 m deep (Figure 6). In profile, CS1 has concave-up and broadly symmetric margins which truncate the underlying planar strata (Figure 7c) with a subhorizontal planar central base section (Figure 7d). The scour only shallowly erodes into the underlying strata, with a maximum apparent margin dip of $\sim 14^\circ$ – $\sim 16^\circ$. The scour occurs between $-3,836$ and $-3,832$ m elevation.

This scour morphology is consistent and simple; there are no deviations exceeding centimeter-scale amplitudes in the concave-up morphology of the scour paleo-surface. Scour fill consists of two components (Figure 6c): a basal section of low-angle inclined bedsets which conformably drape across the scour surface and an overlying section of light-toned strata lacking distinct bounding surfaces.

The basal section is distinguished by 1 and 2 m thick bedsets of light-toned strata separated by prominent bounding surfaces that form resistant bands that drape the scour's paleo-surface (Figure 7). The lowermost bedset is inferred to downlap onto the flat central portion of the basal scour contact, while the upper sets are inferred to onlap onto the scour's southern margin (Figure 6). The strata within each set are light-toned, broadly conforming to the lower bounding surface, and are truncated by overlying bounding surfaces (Figure 7e). The lowermost sets exhibit local undulations within the middle-basal portion of the scour (Figure 7d) which contrasts with the overlying and underlying bounding surfaces. In one location these undulating strata are truncated by the upper bounding surface (Figure 7e).

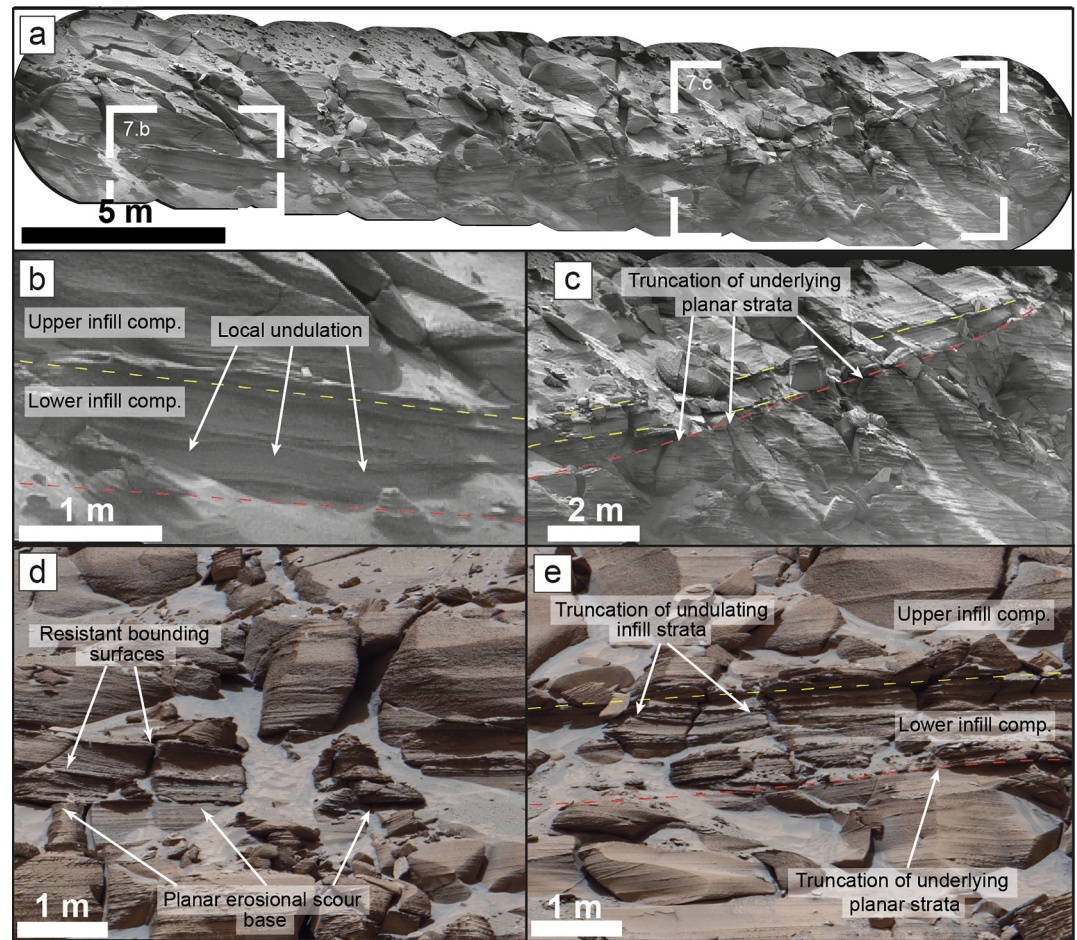


Figure 7. Details of Chenapau Scour 1 architecture. (a) A Long Distance Remote Micro-Imager (LD RMI) mosaic of Chenapau Scour 1 (ccam_05671, acquired on Sol 3671, at Sol 3667 end-of-drive location). (b) Detail showing the local undulation in scour-infill bedset. (c) Detail showing the scour surface truncating the underlying bedding. (d) Mastcam detail of 6.b showing the scour surface is locally planar and parallel to the underlying bedding. (e) Mastcam detail of 6.b showing that the scour-fill bedding undulates and is truncated by overlying scour-fill bedding. Image credits: (a–c) NASA/JPL/LANL/CNES/IRAP; (d–e) NASA/JPL-Caltech/MSSS.

The light-toned fill section contains strata with low-angle dips which gradually decrease stratigraphically upwards until this section is indistinguishable from the light-toned unit (Section 4) in non-scoured sections of the stratigraphy (Figures 6b and 6c). The resistant bands are also gradually lost.

5.1.1.2. *Chenapau Scour 2 (CS2)*

CS2 is present on the southern side of the western face of Chenapau and measures ~41 m in width and ~3 m in depth. The scour occurs between –3,834 and –3,829 elevation. It has a relatively simple, symmetric concave-up profile, with scour margins exhibiting maximum apparent dips of 16–18° grading onto a central planar base (Figure 8). The planar base locally deviates from a concave-up morphology with a centimeter scale erosional low in the scour surface (Figure 8d).

The scour infill is composed of two components. The lower fill section, ~0.5 m thick, is composed of bedsets of light-toned strata conforming to the northern margin and scour base. Bounding surfaces that separate these bedsets appear as prominent bands and become less prominent along the northern margin, although strata remain conformable to the base (Figure 8c). Bedsets within the central portion stack both vertically and laterally northwards along dip. Bounding surfaces truncate underlying bedsets in two locations (Figure 8d) and continue downdip until they intersect the basal contact and incise planar strata underlying the scour. The strata within the

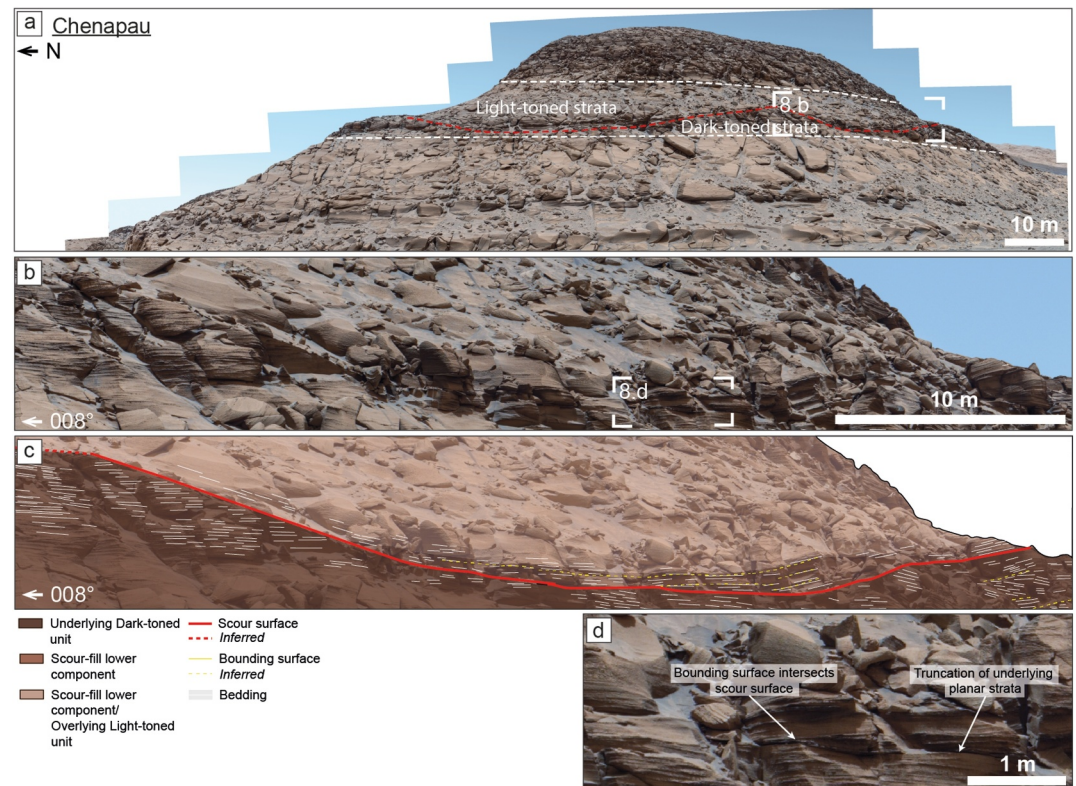


Figure 8. Architecture of Chenapau Scour 2 (CS2). (a) Mastcam mosaic of Chenapau butte illustrating the stratigraphic contacts (white dashed lines) and locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcaml03485 acquired on Sol 3727, at Sol 3724 end-of-drive location). (b) Detail showing CS2 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. (d) Detail showing intersection of the basal scour erosion surface by a bounding surface from within the scour-fill. Image credits: NASA/JPL-Caltech/MSSS.

bedsets are light-toned, recessive, and conform to the bounding surfaces. Undulation of the bedsets or internal strata are not observed in this scour-and-fill structure. The upper fill section of CS2 is recessive and light-toned and is distinguished from the lower fill section by the lack of distinct sets. This section becomes progressively more planar vertically upwards until it is indistinguishable from the overlying "light-toned" unit.

5.1.1.3. Orinoco Scour 2 (OS2)

OS2 occurs on the western face of Orinoco butte and exhibits a cross-sectional profile measuring ~62 m wide, ~4 m thick. It is a single, simple, concave-up scour surface with a symmetric and uniform morphology (Figure 9). The scour margins exhibit maximum apparent dips between 8 and 10° relative to the underlying planar strata. The central base is parallel to the underlying strata. This was the most distant (~300 m range) scour-and-fill structure imaged by the rover in this study, with spatial sampling at ~22.2 mm/pixel.

Lower and upper infill components are observed within OS2. The lower fill is composed of bedsets of light-toned, recessive strata separated by resistant bands conforming to the scour surface. The resistant bands are progressively lost southward across the southern scour margin. The bedsets themselves appear to downlap onto the central scour base, and onlap the southern margin, giving the appearance of stacking laterally to the south. Toward the northern margin, the scour appears overfilled and strata become planar and can be traced outside the confines of the scour. The upper fill is composed of light-toned strata with similar erosional expression to strata confined within bedsets in the lower scour fill. At this resolution, the upper fill strata appear structureless and indeterminate from the overlying light-toned unit.

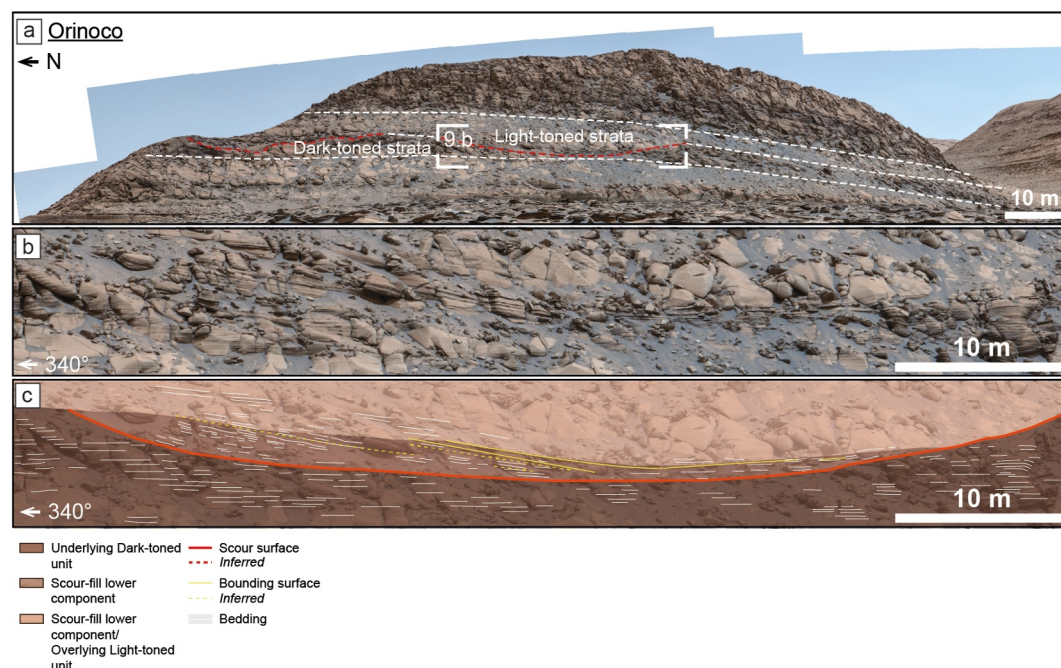


Figure 9. Architecture of Orinoco Scour 2 (OS2). (a) Mastcam panorama of the Orinoco butte illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcam102672 acquired on Sol 3578, at Sol 3576 end-of-drive location). (b) Detail of OS2 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. Image credits: NASA/JPL-Caltech/MSSS.

5.1.1.4. Chenapau Eastern Face Scour (CS3)

CS3 occurs on the eastern face of Chenapau. Interpretation of this outcrop is challenging due to coverage by float blocks, coarse imaging scale, and a strongly foreshortened perspective. Truncation of the underlying strata was not directly observed; the scour is inferred from light-toned strata with apparent dips differing from the underlying, planar dark-toned strata (Figure 10). The erosional surface was inferred from the extent of the changes in apparent dip and measured to be ~ 37 m wide and ~ 2 m thick. The scour occurs between elevations $\sim -3,834$ and $-3,832$ m.

A two-component infill succession is observed. The lower component is comprised of inclined sets of light-toned strata divided by dark-toned bands. The upper component is light-toned and indistinguishable from the overlying unit (Figure 10). At the northernmost part of the butte, the light-toned strata dip southwards. Toward the south, strata first flatten out before becoming increasingly inclined northwards, giving the appearance of a concave-up scour fill similar to CS1 and CS2. Figure 10 shows a distinct surface between these inclined strata and the underlying dark-toned appearing strata at the center which appear parallel to the underlying strata.

5.1.2. Interpretation

We find that CS1, CS2, CS3, and OS2 all share a uniform scour morphology with apparent width to thickness ratios (W/T) of > 15 and a similar two-component scour infill characteristic. The similarity of these scour-and-fill structures suggests shared erosional and depositional processes. As scour-and-fill structures CS1, CS2, CS3, and OS2 all occur within the same stratigraphic interval between the dark- and light-toned stratigraphic units, within ~ 9 m of topographic elevation over a 0.25 km² area (Figure 4; Table 1), we interpret that they all formed during the same narrow temporal window.

The light-toned sets observed in the lower component of the scour fill closely resemble the upper component, with the key distinction being the presence of resistant bounding surfaces (Figure 7d). While local undulations in the lower component bedsets were observed, these only occur at the base of CS1 (Figures 7b and 7e). Thus, we interpret this undulation as a localized depositional texture, such as an expression of microtopography along the scour base, and not representative of typical class A infill. Truncation of these undulating bedsets from overlying bounding

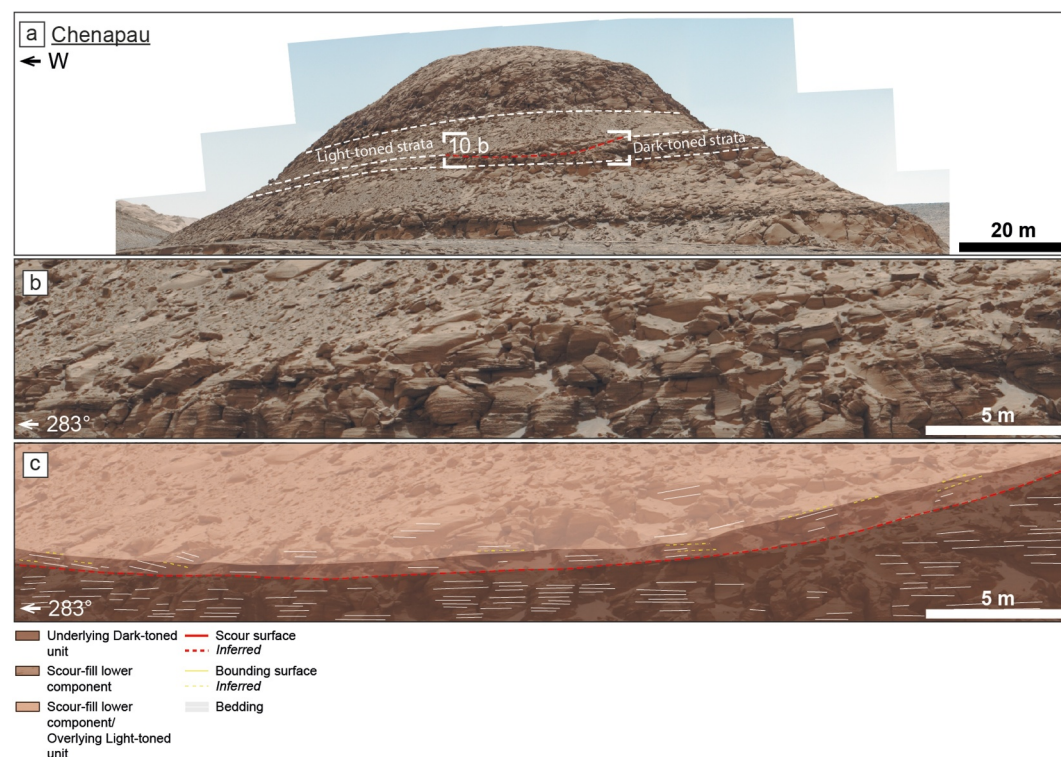


Figure 10. Architecture of Chenapau Scour 3 (CS3). (a) Mastcam panorama of the eastern face of the Chenapau butte illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcam102724, acquired on Sol 3589, at Sol 3579 end-of-drive location). (b) Detail of CS3 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. Image credits: NASA/JPL-Caltech/MSSS.

surfaces indicate that this process occurred contemporaneously with infill deposition. While the resistant bands are often found in association with bounding surfaces, they are also found to separate the sets of light-toned strata (Figure 7d). These inclined resistant-strata-bound sets are interpreted to have a slope-dependent relationship.

The similarity in sedimentary texture, tone, and erosional expression between the upper component of the scour fills of CS1, CS2, OS1, and CS3 (Figures 6–13) and the scour-enclosing strata leads us to interpret a similar depositional process for all. This interpretation is reinforced by the observed continuity of beds and laminations between the upper component of the scour fill and the scour-enclosing stratigraphy. The upper component and the surrounding stratigraphy merge seamlessly together with no observed truncations or interruptions both stratigraphically upwards and laterally beyond the extent of these scour-and-fill structures (Figures 6–11).

The three-dimensional scour surface morphology is difficult to characterize due to the limited range of outcrop exposure orientations. CS3 (Figures 3b and 3c) occurs on the opposite side of the Chenapau butte to CS1 (Figures 3b and 3c). A reasonable assumption is that these two cliff sections intersect the same three-dimensional scour plane. The width and depth of CS3 is much smaller compared to CS1. We infer that the scour exhibits spatial variability in depth and width, and that the CS3 outcrop intersects the scour at a particularly narrow section.

5.2. Class A Scour-and-Fill Structures With a Complex Morphology and Light-Toned Infill

5.2.1. Observations

5.2.1.1. Orinoco Scour 1 (OS1)

OS1 occurs to the north of the western face of Orinoco. In profile, it erosively truncates planar strata of a dark-toned unit (Figure 11). Only the southern margin and basal portion of the structure is preserved with a total preserved extent of ~40 m and depth of ~6 m between elevations of –3,832 and –3,838 m.

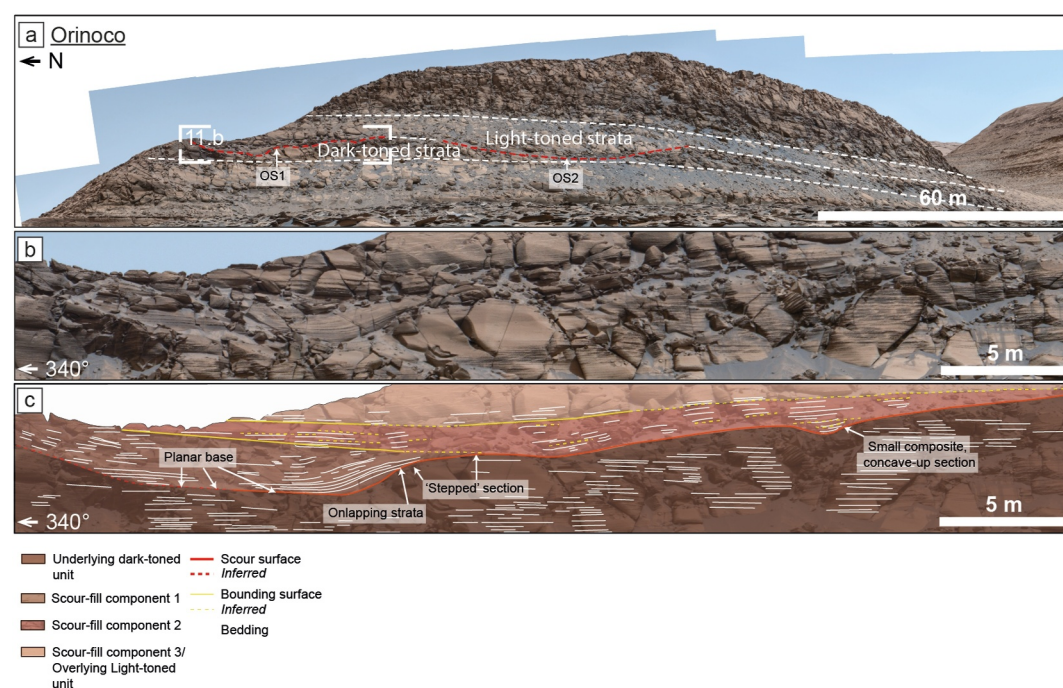


Figure 11. Architecture of Orinoco Scour 1 (OS1). (a) Mastcam panorama of the Orinoco butte illustrating the stratigraphic contacts (white dashed lines) and the location of the OS1's erosive base (red dashed lines), north of OS2 (Mastcam mosaic MR_mc102672 acquired on Sol 3578, at Sol 3576 end-of-drive location). (b) Detail showing OS1 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop as described in the text. Image credits: NASA/JPL-Caltech/MSSS.

The preserved scour paleo-surface is concave-up but the southern margin shows a complex geometry consisting of a stepped section climbing southwards with a small composite, concave-up section, truncating the underlying planar stratigraphy (Figure 11c). The first step (~21 m in width) comprises the lowermost section (Figure 12). This section exhibits a planar base which gradually slopes upward into an inclined surface reaching a maximum apparent dip of 21°. The inclined surface gradually flattens out, again becoming parallel with the underlying strata to form a second step (Figure 11c). Toward the south, this surface gradually slopes upwards to reach a maximum dip of 11° (spread over the next ~12 m of section). The final section of the scour surface exhibits another small, composite, concave-up section, ~4 m in width.

The scour fill is composed of light-toned, recessive-resistant packages in three components: a lower, middle, and upper fill (Figure 11c). The lower fill consists of recessive-resistant packages which drape the lowermost section of the scour surface and onlaps laterally onto the inclined portion of the first step (Figure 12). This fill is sharply truncated by a bounding surface that merges laterally into the basal concave surface of the scour-and-fill structure, aligning with the second step. The middle fill drapes the underlying bounding surface and the second step (Figures 11c and 12b). It is characterized by prominent bands interspersed with recessive packages, with the number of bands decreasing upward within this component. An additional concave-up bounding surface truncates the middle fill. The upper fill drapes this sharp contact with the middle fill component (Figure 11c) and has a distinct light-toned, recessive appearance in which individual strata are not resolved, and which is indistinguishable from the overlying scour-enclosing strata.

5.2.1.2. Bela Vista Scour (BVS)

A prominent erosional surface is present at the top of the western face of a butte, Bela Vista, consisting of the diagenetically overprinted unit. This erosional surface takes the form of a concave-up, scour-shaped feature (Figure 13). The surface extends to the outcrop edge and any continuation of this surface beyond the limit of the butte is not preserved. The remnant structure is ~16 m in width, ~1 m deep, and occurs at elevations between ~−3,842 and ~−3843 m. Due to diagenetic alteration, none of the original underlying stratigraphy or sedimentary

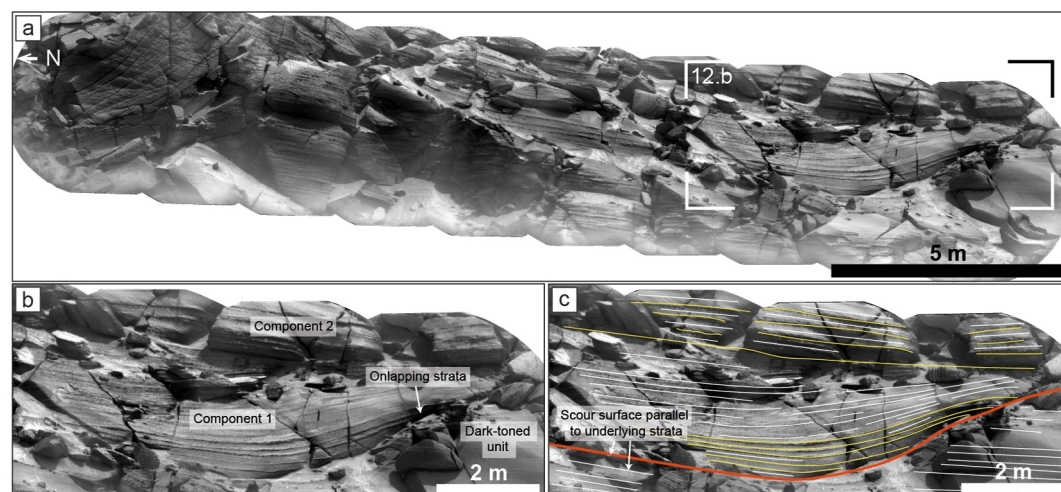


Figure 12. Details of Orinoco Scour 1 (OS1). (a) Long Distance Remote Micro-Imager (LD RMI) mosaic of component 1 of OS1 (LD RMI mosaic ccam_04582, acquired on Sol 3582, at Sol 3579 end-of-drive location). (b) Detail showing how the infill of component 1 onlaps onto the scour surface and is truncated by component 2. (c) Interpretation showing the scour surface (red), bounding surfaces (yellow), and bedding (white). Image credits: NASA/JPL/LANL/CNES/IRAP.

features can be discerned. This scour is distinct from other scours in class A as the central portion is smaller, arcuate and not planar.

Despite apparent diagenetic alteration of scour infill, bedding or potential third-order bounding surfaces can be delineated and appear to drape across the scour surface (Figure 13). In one location, one of these interpreted third-

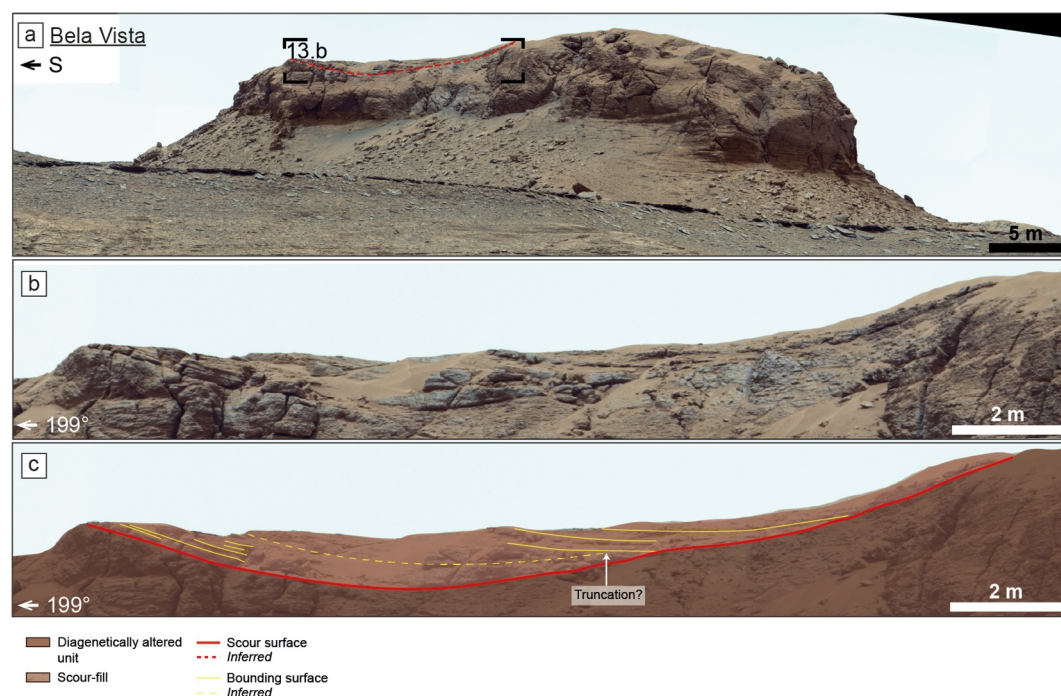


Figure 13. Architecture of Bela Vista Scour (BVS). (a) Mastcam panorama of the Bela Vista butte illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mc102968, acquired on Sol 3635, at Sol 3633 end-of-drive location). (b) Detail showing BVS uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. Image credits: NASA/JPL-Caltech/MSSS.

order bounding surfaces of the scour fill is truncated by a concave-up, simple, second-order bounding surface which appears to converge laterally, gradually merging with the basal concave surface of the structure.

5.2.2. Interpretation

We interpret OS1 and BVS as a complex of stacked scour-and-fill structures formed by amalgamation of simple, smaller scour-and-fill structures. This interpretation is supported by the observation of distinct erosional surfaces or second-order bounding surfaces truncating the scour infill (Figures 11c and 13c) that appear to merge with the underlying basal scour-surface. In OS1, these surfaces are also associated with each of the three “stepped” concave sections of the scour surface (Figure 11) and are thus interpreted to form the shape of three stacked scour-and-fill structures. When OS1 and BVS are divided into individual stacked scour components, the scour bases themselves are simple, concave-up, broad, and OS1 even contains a planar basal section. These characteristics are similar to the morphology of the basal scour surfaces exhibited in Section 5.1.

We also note a similar scour fill conforming relation in OS1 and BVS to the scours in Section 5.1. The infills of OS1 and BVS also conform to the underlying scour surface or erosional bounding surfaces (Figure 12). Corroborating this, we also observe an upper component in OS1 which shares a similar light-tone and texture to the upper component infill within scour-and-fill structures in Section 5.1. Therefore, our interpretation leads us to the conclusion that the infill processes for the stacked scours of OS1 are also comparable to the individual scours in Section 5.1. Hence, we infer that OS1 and BVS may share similarities with the erosional processes of the scours in Section 5.1, albeit with some added complexities. OS1 also occurs in the same stratigraphic interval and within the same ~9 m topographic elevation as CS1, CS2, ES1, ES2, CS3, and OS2. Based on these factors, we suggest that OS1 may have formed during the same episode as the scour-and-fill structures identified in Section 5.1.1.

5.3. Class A Scour-and-Fill Structures That Have Been Exhumed and Contain Minimal to No Preserved Infill

5.3.1. Observations

5.3.1.1. Exhumed Scour 1 (ES1)

ES1 occurs within a distinct ledge present along the southwestern flank of Marker Band valley (Figure 14). It is characterized by a broad, concave-up gap carved into the bedrock, forming a curved surface that appears to incise the underlying stratigraphy (Figure 14b). This curved surface is symmetric and uniform, measuring approximately 40 m in width and 1 m in amplitude, and occurs at elevations ranging from ~−3,834 m to ~−3,832 m (Figure 14). The margins exhibit apparent dips of 12° and 13° relative to the underlying strata, while the central portion of the surface is planar and parallel to the underlying stratigraphy.

Recessed behind the ledge and overlying the interpreted northern margin of the scour is a thin band of preserved bedding inclined at a different angle to strata underlying the scour (Figure 14c). The preserved bedding within this band appears conformable to the scour surface along the northern margin and scour base. No contact is visible, but this may be due to dust coverage, terrain occlusion, and strong foreshortening due to the viewing geometry.

5.3.1.2. Exhumed Scour 2 (ES2)

Directly adjacent to ES1 along the same ledge is a second exhumed scour forming a broad, concave-up gap eroded into bedrock (Figure 15). This feature has a width of ~50 m and amplitude of ~3 m and occurs between ~−3,841 and ~−3,838 m elevation. The scour surface is broad and symmetrical, with preserved scour margins showing apparent dips of ~16° relative to the underlying planar strata. In one location, strata can be traced for ~2 m along a sharp contact with the northern scour margin (Figure 15d). These strata appear to drape the scour's paleo-surface (Figure 15e).

5.3.1.3. Eroded Remnants of an Exhumed Scour 3 (ES3)

Recessed to the west behind ES1 and ES2 is a second stratigraphically overlying ledge. The ledge is inclined to the north, flattening out along an asymptotic base (Figure 16). This inclined morphology strongly resembles a scour margin, thus we infer this feature represents a scour surface. This eroded remnant of a scour surface occurs

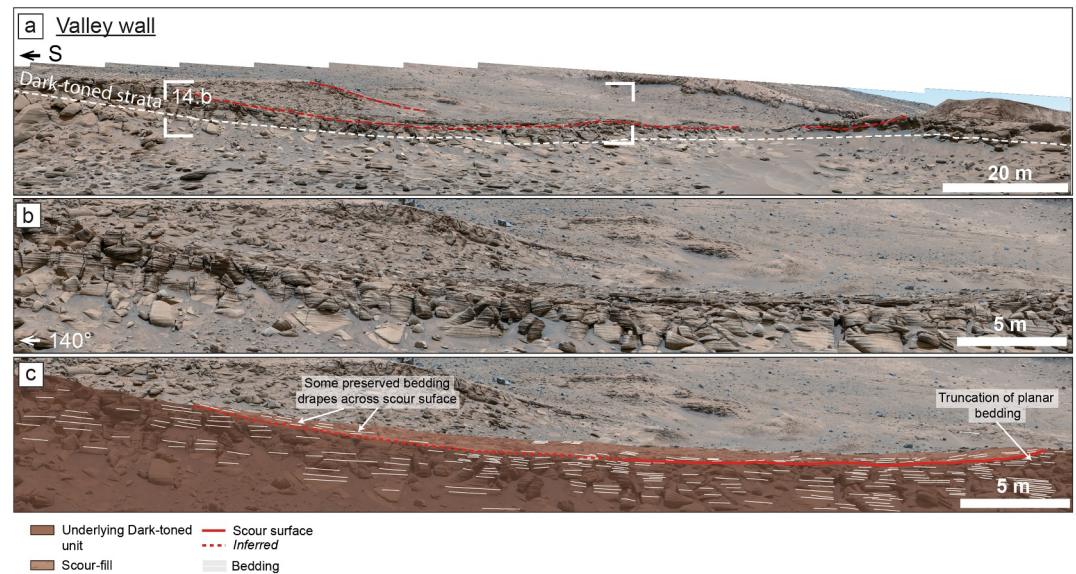


Figure 14. Architecture of Exhumed Scour 1 (ES1). (a) Mastcam panorama of the westernmost wall of Marker Band valley illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcam103501 acquired on Sol 3730, at Sol 3728 end-of-drive location). (b) Detail showing ES1 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop. Image credits: NASA/JPL-Caltech/MSSS.

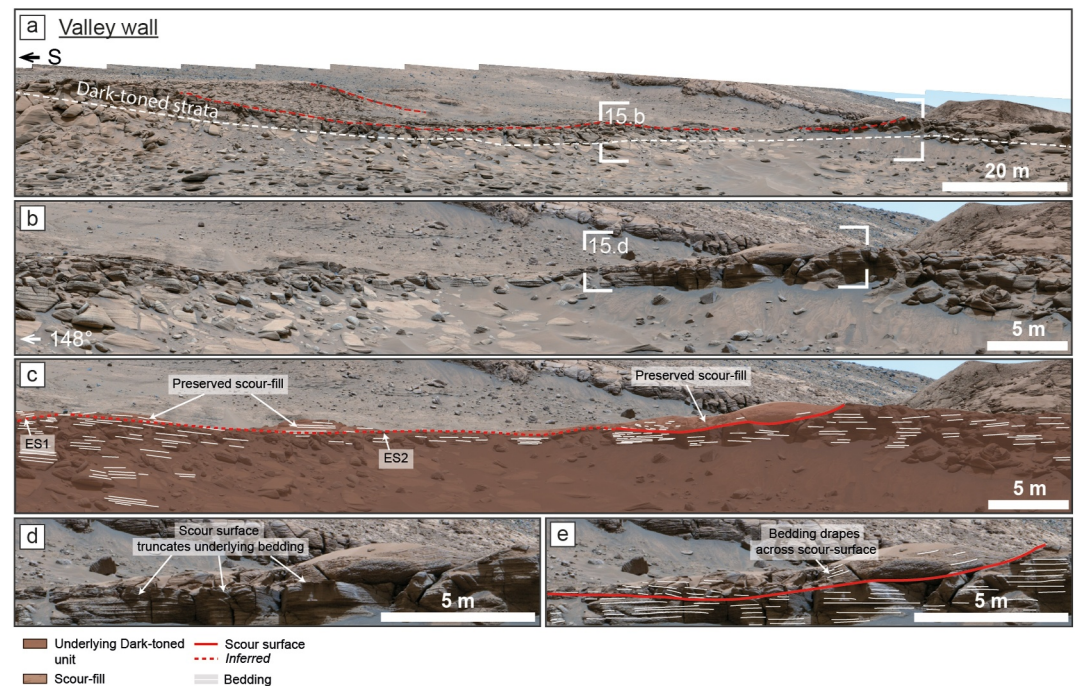


Figure 15. Architecture of Exhumed Scour 2 (ES2). (a) Mastcam panorama of the westernmost wall of Marker Band valley illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcam103501 acquired on Sol 3730, at Sol 3728 end-of-drive location). (b) Detail showing ES2 uninterpreted. (c) Interpretation showing the scour boundaries, bounding surfaces, and stratigraphy mapped in the outcrop as described in the text. (d) Detail showing how the scour surface is observed truncating the underlying bedding and is overlain by partially preserved scour-fill that drapes across the scour surface. (e) Interpretation showing the scour's erosive surface (red) and bedding (white). Image credits: NASA/JPL-Caltech/MSSS.

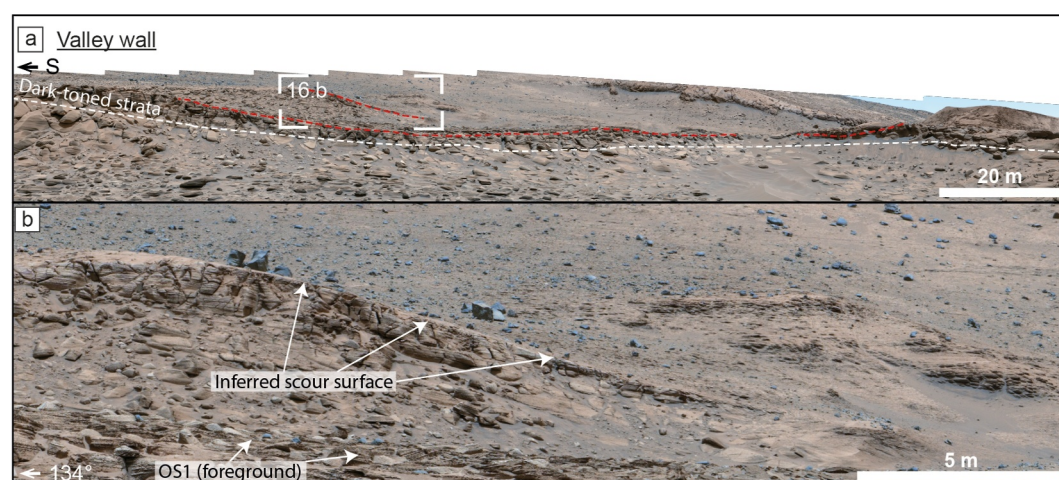


Figure 16. Architecture of Exhumed Scour 3 (ES3). (a) Mastcam panorama of the westernmost wall of Marker Band valley illustrating the stratigraphic contacts (white dashed lines) and the locations of the scour-and-fill structures' erosive bases (red dashed lines) (Mastcam mosaic MR_mcama103501 acquired on Sol 3730, at Sol 3728 end-of-drive location). (b) Detail showing the partially preserved, inferred erosive surface of ES3. Image credits: NASA/JPL-Caltech/MSSS.

at elevations between $-3,819$ m and $-3,823$ m. It has a preserved width of ~ 19 m and an amplitude of ~ 4 m. No infilling strata are observed.

5.3.2. Interpretation

ES1, ES2, and ES3 all exhibit a strong morphological similarity to the scours in Section 5.1, thus we infer a similar formation process. These scours all show a similar range of widths (~ 40 to ~ 62 m) and amplitudes (~ 1 to ~ 4 m) (Table 1). The simple, symmetric, concave-up morphologies are also consistent. The maximum apparent dip of the scour margins of ES1, ES2, and ES3 varies around 12 – 16° which is comparable to the dips of the scour margins in Section 5.1. ES1 and ES2 also exhibit a planar central scour base. Moreover, ES1 and ES2 occur within the same ~ 9 m of elevation as CS1, CS2, CS3, OS1, and OS2 (Table 1). For this reason—and because the exhumed scours truncate into the same stratigraphic interval at similar elevations—we also interpret that scours ES1 and ES2 formed during the same temporal window as CS1, CS2, CES, and OS1.

Where bedding overlies the scour surface in ES1 and ES2, stratification conforms to the underlying scour, mirroring the scour infill characteristics of the scours found in Sections 5.1 and 5.2. Given the draping relationship, similar distinctions in erosion resistance between scour fill and the underlying strata, and as they occur at the same stratigraphic interval, we interpret the depositional processes of ES1 and ES2 to be similar to the scour-and-fill structures in Sections 5.1 and 5.2.

Exhumation of these scours may have been caused by differences in erosional resistance between scour infill and the underlying strata. The infill was likely less resistant to erosion relative to the underlying stratigraphy (e.g., Edgett & Sarkar, 2021) and thus more easily exhumed by weathering processes, leaving the scour-shaped gaps in the underlying dark-toned strata.

5.4. Class B Scour-and-Fill Structures With a Complex, Asymmetric Scour Morphology and Dark-Toned Infill

5.4.1. Observations

5.4.1.1. *Canta Detour Scour (CDS)*

A concave-up scour-and-fill structure containing indurated, dark-toned infill (Figure 17) was observed eroded into the light-toned, diagenetically overprinted unit along the western flank of Marker Band valley. This structure is ~ 7 m in width, < 0.5 m deep, and occurs at ~ -3850 m elevation. While the eastern scour margin is visible, the western margin is self-occluded by outcrop viewing geometry. The lower scour surface forms a singular concave-up scoop along a sharp contact with underlying strata. An additional composite feature is present: an inflection

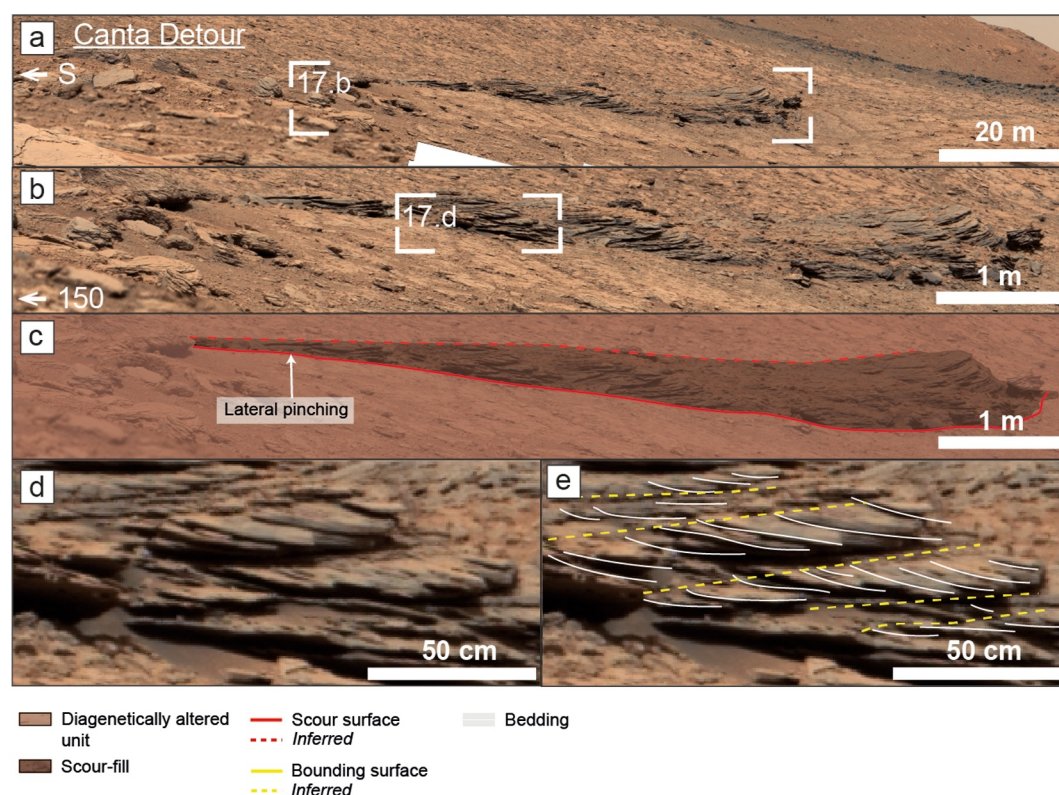


Figure 17. Architecture of Canta Detour Scour (CDS). (a) Mastcam panorama of part of the Canta Detour providing context for the scour-and-fill structures (Mastcam mosaic MR_mcsm103090 acquired on Sol 3653, at Sol 3651 end-of-drive location). (b) Detail showing CDS uninterpreted. (c) Interpretation showing the scour boundaries mapped in the outcrop as described in the text. (d) Detail showing the scour-fill. (e) Interpretation showing the cm-scale cross-bedding as described in the text. Image credits: NASA/JPL-Caltech/MSSS.

point on the eastern scour margin where scour morphology transitions from concave to convex as it pinches out as a wing-shaped structure (Figure 17c).

The dark-toned infill consists of amalgamated bedsets consisting of centimeter-scale tabular cross-stratification dipping to the north-west (Figures 17d and 17e). These sets are consistently truncated by overlying tabular sets. The scour infill contact with the overlying stratigraphy is sharp. The infill appears to be more indurated than the structure-enclosing light-toned recessive strata.

5.4.2. Interpretation

Class B is the most distinctive of the scour-and-fill classes in terms of both morphology and infill characteristics. The strongest difference between CDS, the sole scour in class B, and class A is scale. CDS is ~50 to ~90% smaller than the other scour-and-fill structures described in this study (Table 1). CDS is the sole scour exhibiting a pinching out wing-shape morphology. The infill of CDS is dark-toned, erosionally resistant, and characterized by multistory, erosive decimeter-scale sets. This contrasts with the large-scale, light-toned recessive bedsets conforming to the scour surface observed in class A. These architectural distinctions suggest class B's infill differs from the other scour-and-fill structures and the enclosing aeolian sandsheets. The distinction in erosion resistance and tone suggest that the class B's infill may also compositionally differ from the enclosing aeolian sandsheets. Due to these distinctions in size, morphology, and infill characteristics, we interpret that the processes that scoured and infilled class B were different from the other scours.

6. Hypotheses for Formation of Scour-and-Fill Structures

Ten scour-and-fill structures, and their associated infill where present, have been identified within the Chenapau member of the Mirador formation exposed in Marker Band valley. These structures exhibit a range of

morphologies and may contain light-toned and dark-toned sedimentary infill. Several scour structures in which the infill has been exhumed were also identified (Figure 18). Class A scour-and-fill structures are interpreted to have formed through the same erosional and depositional processes due to similarities in their size, morphology, and scour infill characteristics. The class B scour-and-fill structure is distinct from class A and is discussed separately.

The host stratigraphy facies consisting of planar, uniform-in-thickness, and laterally extensive planar laminae are characteristic of formation by the migration of aeolian wind-ripples (Sections 4.1 and 4.2; e.g., Kocurek & Nielson, 1986). The observation that this facies occurs in planar parallel sub-horizontal bedsets suggests that this represents deposition in an aeolian sandsheet environment (Kocurek & Nielson, 1986). On this basis, we infer that the scour-and-fill structures were formed in an overall aeolian sandsheet setting. Scouring from fluvial processes, bedform migration, and aeolian deflation are all capable of forming scour-and-fill structures in the sedimentary record (e.g., Blakey, 1988; Kocurek & Day, 2018; Priddy & Clarke, 2020). Here, we evaluate and discuss these processes.

6.1. Hypothesis 1: A Fluvial Mechanism for Scour-and-Fill Structures

The distinctive architectural features and facies associations commonly observed in channel scour cross-sections resulting from fluvial erosion are well documented (e.g., Gibling, 2006). In the Chenapau member, the scours exhibit width-to-depth (W/T) ratios of ~ 15 . Fluvial scours with similar width-to-depth ratios are inconsistent with typical channels and instead are commonly associated with shallow channels and sheet-form fluvial deposits found in aeolian environments (Figure 17a; e.g., Gibling, 2006; Priddy & Clarke, 2020). Similar sized, broad, concave-up scours have previously been inferred by Rapin et al. (2021) in the layered sulfate unit in Aeolis Mons from ~ 3 to 6 km away. These observations led Rapin et al. (2021) to interpret these scours as fluvial in origin, however, this interpretation remains open as the facies details could not be fully resolved at such observational distances.

There are a number of expected infill characteristics associated with fluvial scouring in an aeolian environment that are inconsistent with scour class A. Scour-and-fill structures in class A do not contain evidence for lag components with pebbles > 1 cm in diameter—which would likely be visible at most of the scour image resolutions (Table S4 in Supporting Information S1)—and rip up clasts which are often associated with episodic fluvial flooding in aeolian environments (e.g., Banham & Mountney, 2014; Cain & Mountney, 2009; Priddy & Clarke, 2020). The scour infill does not show evidence for centimeter-scale current ripple lamination nor tens of centimeter-scale cross-bedding which would be evidence for migration of dunes within a fluvial channel (e.g., Banham & Mountney, 2014; Cain & Mountney, 2009; Gibling, 2006). Instead, the similarity and the observed continuity of the scour fill of class A with the overlying light-toned, scour-enclosing strata indicates a shared depositional process. With the scour-enclosing strata interpreted to be from the migration of aeolian wind ripples (Section 4.2), we propose an aeolian interpretation for the scour fill.

The morphology of the scour surfaces in class A are inconsistent with fluvial channel morphology. The scours in class A have no clear inflection points or pinch-out into a wing-shape at their lateral extents, a key feature in fluvial architecture caused by processes such as overbank flooding (e.g., Buffington & Montgomery, 2022; Gibling, 2006). The base of the scours are also predominantly smooth with none of the irregularities associated with varying flow rates and resistance found in channels along cross-section (e.g., Charlton, 2007; Wohl, 1998) common in shallow channels and sheet-like deposits in aeolian environments (e.g., Ferronato et al., 2019; Heme de Lacotte & Mountney, 2022; Jaeger et al., 2017; Langford & Chan, 1989; Scherer & Lavina, 2005). The limbs of the scour surfaces in the Chenapau member are also shallow with apparent dips of ~ 10 – 20° , inconsistent with the common “steep” sides recorded by Gibling (2006) for paleochannels in aeolian settings. As the scours in class A are inconsistent with characteristics typical from fluvial scouring, we infer that they likely formed by a different erosional process.

The distinct morphology and infill characteristics of scour-and-fill structure class B, however, are consistent with fluvial scouring in an aeolian environment. The inferred asymmetry of the central body and isolation to any other similar scour forms may indicate deposition in a channelized, single-threaded river (e.g., Engel & Rhoads, 2012; Gibling, 2006; Thornbury, 1954). The pinching out seen in the southern flank of CDS is characteristic of channel wings formed through aqueous scouring in channels from overbank flooding (e.g., Buffington & Montgomery, 2022; Gibling, 2006). The width-to-thickness ratio of ~ 14 observed in class B supports the interpretation of a small, shallow fluvial channel formed by fluvial processes within aeolian environments (e.g., Gibling, 2006).

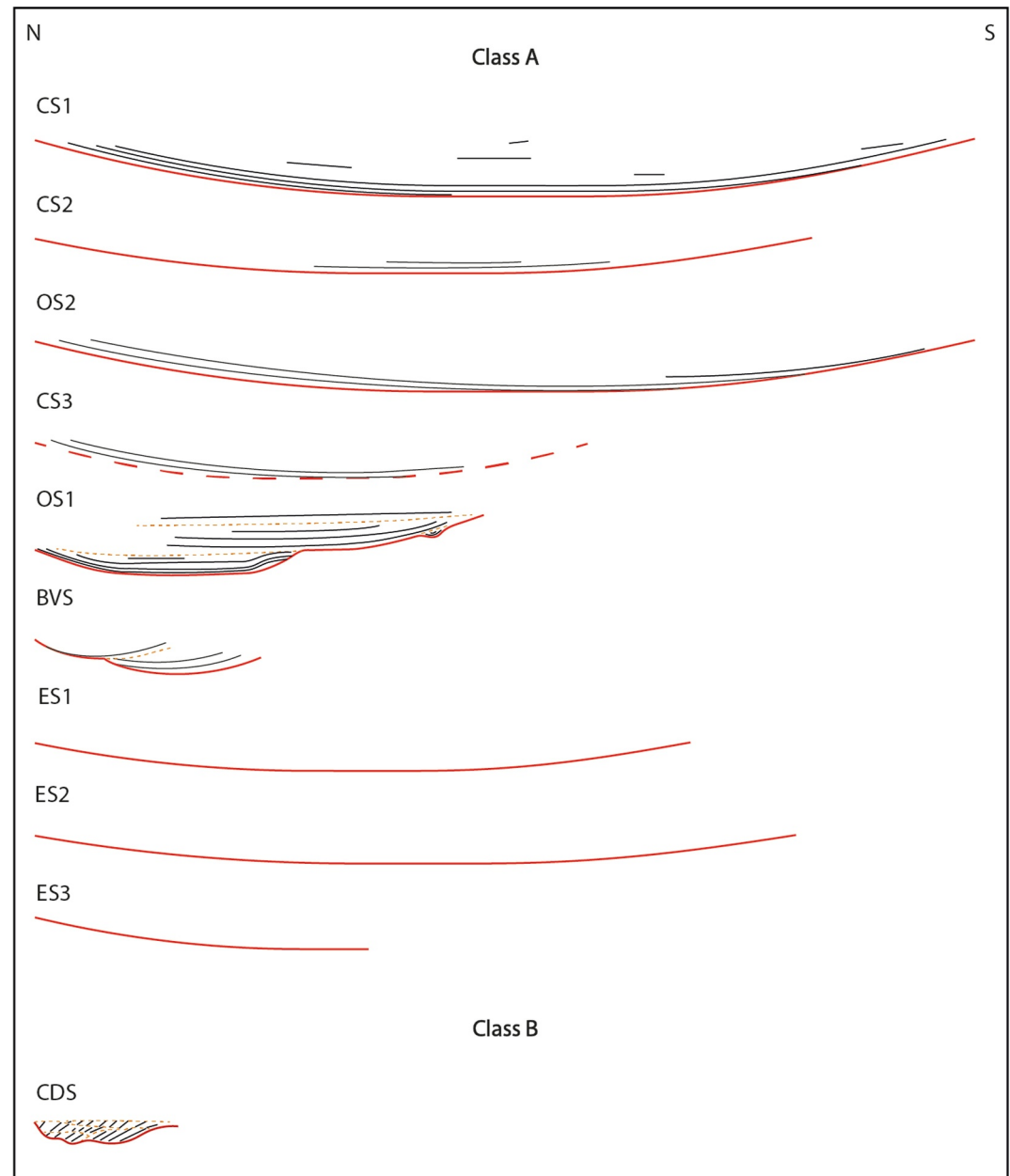


Figure 18. Reconstructed geometry of each of the scour-and-fill structures to scale. Scour surface is in red, strata is in black and bounding surfaces (when appropriate) are in orange. Dashed lines show inferred geometries. Note the size difference and scour-fill architecture between classes A and B.

The distinctive, amalgamated bedsets of cm-scale tabular cross-stratification are consistent with infilling by fluvial dune migration (e.g., Gibling, 2006). The darker tone and induration of the scour fill in class B, compared to the surrounding stratigraphy and scours, suggest a distinct sediment infill or even provenance relative to the adjacent strata. Class B also aligns with several meter-scale, dark-toned, indurated lenses interstratified with aeolian dunes in the Contigo member interpreted to be aqueous lenses (Figure 2; Caravaca, Le Mouelic, et al., 2022; Gupta et al., 2022). While class B represents an aqueous depositional environment, the distinction in scour architecture to class A implies different formative mechanisms and sedimentary processes for the rest of the scours.

6.2. Hypothesis 2: Aeolian Bedform Migration as a Mechanism for Scour-and-Fill Structures

One plausible hypothesis for the formation of the scour-and-fill structures is by aeolian dune migration (Figure 17b; e.g., Cardenas et al., 2022; Kocurek & Havholm, 1993; Mesquita et al., 2021; Mountney & Thompson, 2002; Swanson et al., 2019). In this mechanism, the erosion of the scour surface is created by migration of troughs leeward of a migrating dune which gets progressively infilled as the bedform migrates into the scour. Dune deposits can occur as concave-up scour-and-fill structures when the overall angle of bedform climb—determined by the balance between erosion and deposition—is low but fluctuates over shorter time scales (Figure 17b; Abrantes et al., 2020; Kocurek & Day, 2018; Kocurek & Havholm, 1993; Mesquita et al., 2021; Mountney & Thompson, 2002). Alternatively, migration of three-dimensional dunes with laterally variable scour depths can result in especially deep troughs being preferentially preserved as scour-and-fill structures (Cardenas et al., 2019; Swanson et al., 2019). However, we find that class A scour-and-fill structures are distinct from those predicted by bedform migration. Scour-and-fill structures from bedform migration likely contain evidence of cross-bedding—tangential, tabular (Cardenas et al., 2019; Hasiotis et al., 2021; Kocurek & Day, 2018; Mesquita et al., 2021; Mountney & Thompson, 2002) or trough-shaped (Abrantes et al., 2020)—along with clear truncation of the scour fill by overlying dune or interdune deposits. The infill within class A scour-and-fill structures, however, although superficially similar to trough cross-bedding, lacks these clear truncation surfaces (Figure 19b), suggesting that class A does not contain a discrete, trough cross-bedded set. Instead, class A scour-and-fill structures appear overfilled with an infill that seamlessly merges with the overlying and surrounding stratigraphy (Section 5.1.2). The continuity in sedimentary texture, tone, and erosional patterns between the upper component of the scour fill—where preserved—and the surrounding sandsheet facies (Section 4) supports an interpretation of sandsheet migration into a pre-existing topographic low. Additionally, class A scour-and-fill structures are laterally isolated, whereas scour-and-fill structures formed by aeolian bedform migration would likely result from a field of bedforms. These features often display lateral truncation between adjacent scours (e.g., Cardenas et al., 2019), a characteristic that is absent in class A scour-and-fill structures. Therefore, we argue that it is unlikely the scours in the Chenapau member were caused by bedform migration.

6.3. Hypothesis 3: Scour Formation by Aeolian Blowouts

An alternative hypothesis for formation of the scour-and-fill structures is by aeolian blowout deflation (Figure 17c; Blakey, 1988; Gradzinski, 1992; Hesp, 2002; Warner et al., 2022). Blowouts are depressions or hollows formed through localized removal of sediment by wind erosion of a stabilized surface in an arid to semi-arid setting (Hesp, 1996, 2002). Although vegetation often acts as the stabilizing agent on Earth, blowouts also occur in regions with little-to-no observed vegetation, where other surface stabilizing mechanisms such as cementation, lag deposits, and subsurface ice dominate (Hesp, 2002; Hesp & Hyde, 1996). The concave-up scours in the Chenapau member resemble 2D cross sections through saucer-shaped blowout structures (e.g., Hesp & Walker, 2013). The widths and thicknesses of the scours have comparable diameters and depths to blowout structures observed on Earth (e.g., Baird et al., 2021; Hugenholtz & Wolfe, 2006). Recognizing blowout depressions in the rock record can be challenging due to a lack of outcrop continuity (e.g., Blakey, 1988; Ferronato et al., 2019; Gradzinski, 1992), yet these features are commonly observed in Holocene and present-day aeolian geomorphology (e.g., Hesp, 2002) and have been extensively studied. We can compare terrestrial blowouts to the Gale scour-and-fill structures by drawing on studies of the geomorphology and settings of recently active blowouts (e.g., Abhar et al., 2015; Hesp, 2002; Hugenholtz & Wolfe, 2009), their facies associations and architecture from ground penetrating radar (GPR) surveys (e.g., Jewell et al., 2017; Pedersen & Clemmensen, 2005; Warner et al., 2022) and examples from the rock record (e.g., Blakey, 1988; Ferronato et al., 2019; Gradzinski, 1992).

6.3.1. Blowout Erosional Deflation Processes

The broad, consistent, symmetric, concave-up morphologies and flat bases exhibited by the scour-and-fill structures are characteristic of processes that form blowouts. The distinctive regular, symmetric morphologies of the “saucer” and “bowl” blowout types is a product of a morphology and wind-flow feedback loop, where a wind-steering effect induced by the rounded blowout walls creates a re-circulation cell (Hesp & Walker, 2012; Hugenholtz & Wolfe, 2009). This process, while removing most sediment from the blowout, also redistributes sediment from the deflation around the “saucer,” maintaining the characteristic, symmetric, consistently semi-circular depression and gradually evening out any irregularities in shape (Hesp, 2002; Hesp et al., 2017;

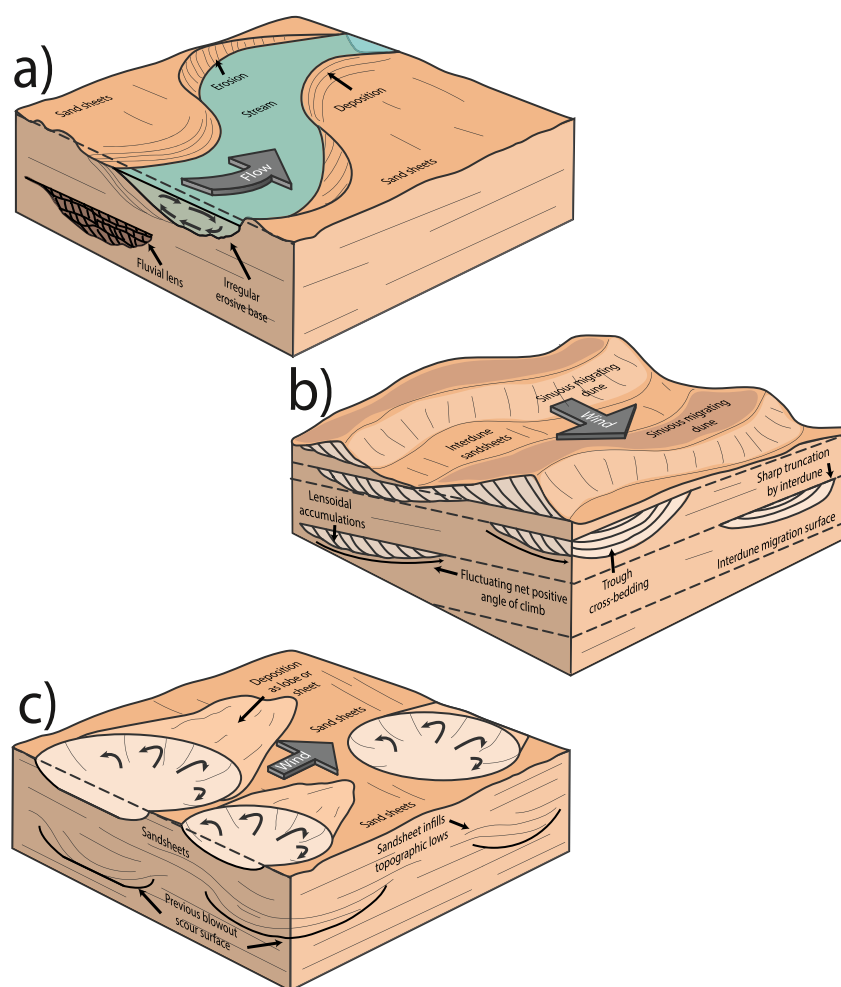


Figure 19. Schematic showing scenarios for scour-and-fill structure formation. (a) Scouring through aqueous processes. (b) Scouring through bedform migration. (c) Scouring through localized wind deflation.

Hugenholtz & Wolfe, 2009). The flat bases exhibited by the Chenapau member scours are similar to flat surfaces which form in blowouts when wind deflation, and thus the depth of a scour, meets a stabilized surface lower down in the stratigraphy such as a hard, indurated layer or the water table (e.g., Hesp & Walker, 2013). In these instances, Hesp and Walker (2012) found that a blowout would expand laterally, rather than vertically downward, forming a flat base. These broad, consistent, concave-up and planar base features are characteristic of blowout cross-sections identified within the rock record (Feronatto et al., 2019; Gradzinski, 1992) and from GPR surveys (e.g., Jewell et al., 2017; Pedersen & Clemmensen, 2005; Warner et al., 2022). For these reasons, we find that the Chenapau member scour-and-fill structures have morphologies consistent with blowout scour formation.

6.3.2. Blowout Infilling Processes

The onlapping, downlapping and conformable relationships of the inclined bedsets from the lower component of the scour fills indicate that infill occurred following scour formation. Multiple field examples describe blowout infill with inclined bedsets conformable with the scour base and onlapping/downlapping relationships in both modern ground penetrating radar surveys (e.g., Neal & Roberts, 2001; Pedersen & Clemmensen, 2005; Warner et al., 2022) and in the rock record (e.g., Feronatto et al., 2019; Gradzinski, 1992; Mountney, 2006b). In the latter, Feronatto et al. (2019) and Gradzinski (1992) observed wind-ripple, grain-flow, and grain-fall strata within inclined cross-strata which infilled blowouts which led these authors to an interpretation that the inclined cross-sets were formed by dunes—possibly parabolic or crescentic—building into and migrating across the blowout. Warner et al. (2022) proposed a similar dune migration process for cross-stratified blowout-infills from GPR studies of

Holocene blowouts. The upper range of apparent dips of the lower fill component of the scour-and-fill structures are similar to the apparent dips identified within the GPR cross-sections of the blowout infill in Warner et al. (2022).

While the resolution of our data is limited and we cannot resolve sedimentary textures indicative of grain-flow or grain-fall strata like Ferronato et al. (2019) and Gradzinski (1992), we did observe bands separating the downlapping and onlapping sets. These bands were comparatively more erosionally resistant than the more recessive light-toned sets and showed some truncation of underlying sets, evidence of reactivation. The observed differences in the erosional resistance is likely a result of the complex interplay between grain packing, grain size, and cementation (Banham, Gupta, et al., 2024; Besly et al., 2018). We speculate that the differences in resistance could represent changes in sedimentary texture from slope depositional processes found in migrating dunes. However, unlike the inclined cross-sets interpreted as dune cross-stratification from the rock record (e.g., Ferronato et al., 2019; Gradzinski, 1992; Mountney, 2006b) and GPR surveys (Warner et al., 2022), the lower component bedsets identified in our data make up less than 25% of the scour fill component, do not show truncation from the scour-enclosing strata, and drape across the entirety of the underlying scour surface rather than exhibit lateral migration at dips parallel to one of the scour limbs.

The light-toned, recessive, planar upper scour fill component which we interpret as wind-ripple laminae from a sandsheet environment (Section 5.1.2) holds some similarities to the fill of blowouts in the rock record. Both Ferronato et al. (2019) and Gradzinski (1992) identified blowouts with “an over-filled appearance” exhibiting a transition from inclined cross-stratification to more planar strata across the top of the scour margin. Based on these observations, Ferronato et al. (2019) interpreted the aeolian sandsheets to be laterally continuous with aeolian dunes that filled the blowouts. Similar to Ferronato et al. (2019), we find that sandsheets are laterally continuous with the inclined cosets infilling the blowouts. We find that the resistant bands defining our lower scour fill component are lost up section and the scours are filled with the upper component comprised of sandsheet strata making up the rest of the 75% of the scour fill.

6.3.3. Blowout Amalgamation Processes

OS1 is interpreted to represent a multistory body formed by three stacked scour-and-fill structures (Section 5.3.2) which form three distinct steps in the southern scour limb as the scours vary in thickness and width (Figures 15 and 17). Similar stepped patterns are found in active blowouts and found to be caused by blowout amalgamation (A. Smith et al., 2017). Saucer and bowl blowout amalgamation is a common process in blowout development (e.g., Abhar et al., 2015; A. Smith et al., 2017). Abhar et al. (2015) used satellite data to show complex blowout bodies formed from the amalgamation of individual blowouts. A. Smith et al. (2017) observed active blowout amalgamation where a saucer blowout was captured by an adjacent bowl blowout over a period of 3 years. Amalgamated blowouts have also been identified in the rock record (Ferronato et al., 2019), and through GPR studies (Pedersen & Clemmensen, 2005). Our observations of multistory blowouts are consistent with formation by amalgamation of laterally adjacent blowout structures.

6.3.4. Scour-Enclosing Environment and Blowout Initiation

Blowouts can occur in a multitude of arid to semi-arid landscapes including coastal settings (Abhar et al., 2015; Hesp, 2002; Warner et al., 2022), lakesides (Neal & Roberts, 2001), playas (Allen & Anderson, 2000; Goudie, 2023), inland deserts (Hesp, 1996), and even in the sub-arctic (Kayhko, 2007). Saucer-shaped blowouts are often associated with sandsheet environments in both modern (Hesp, 2002; Hugenholtz et al., 2007; Kocurek & Nielson, 1986) and ancient examples (e.g., Ferronato et al., 2019; Gradzinski, 1992). Sandsheets are considered to form in specific aeolian environments where dune development is inhibited by processes such as near-surface cementation, a high water table, armoring of the surface by lag deposits, or vegetation which all raise the threshold velocity of sand entrainment (Kocurek & Nielson, 1986). Here, evidence of episodic surface water identified throughout the Mirador formation (Caravaca, Le Mouelic, et al., 2022; Gupta, Dietrich, Lewis, Mondro, et al., 2023) and within the study area supports either a high water table or near-surface cementation as the process supporting sandsheet development (Section 4.2). The environments conducive to sandsheet formation also act to inhibit wind entrainment of sand (Kocurek & Nielson, 1986) and thus could act as a stabilizing surface, meeting one of the conditions for blowout formation.

The cause of initiation and development of the scour-and-fill structures within the Chenapau member is unclear. Wind has been observed (Hesp & Hyde, 1996) and modeled (Barchyn & Hugenholtz, 2013) to generate small-

scale, localized, negative topographic change during a single event on a stabilized surface. Subsequent wind erosion can then exploit this localized negative topography, sustain deflation, and lead to formation of large-scale blowout structures (Hugenholtz & Wolfe, 2006; Smyth et al., 2013, 2019). It is conceivable that a similar process may have been responsible for the scour-and-fill structures within the Chenapau member.

6.4. Evolutionary Model for Scour-and-Fill Structure Formation

We present the following scenario as a possible sequence of events in the erosional and depositional history of the scours:

1. Previously established sandsheets were stabilized or partially stabilized by either early syndepositional near-surface cementation or water-table fluctuations.
2. Strong winds cause partial deflation creating an uneven topography and small proto-blowouts.
3. Sustained, high-velocity winds with low sediment-saturation caused reworking and continued deflation of these blowouts to form the broad, saucer shapes.
4. Amalgamation of adjacent blowouts.
5. Migration of sandsheets over and into the blowouts.
6. Covering of blowout structures and blowout infill by sandsheet migration.

7. Scour-and-Fill Structures as Evidence for Intensification of Wind Regime

Although most of the literature on the morphology of blowouts focuses on biotic and anthropomorphic processes driving blowout initiation, one of the key abiotic precursor processes for blowouts formation are prolonged or episodic intense and undersaturated winds (Hesp, 2002). In regions with little to no vegetation, Hesp and Hyde (1996) observed that 1–3 m wide to 0.5–1 m deep saucer blowouts were initiated during a 10 hr long gale. Subsequent field studies have also identified high velocity winds as integral to blowout morphology and development in sparsely vegetated regions (Abhar et al., 2015; Levin, 2011; Luo, Wang, Lu, et al., 2019; Luo, Wang, Shao, et al., 2019). Modeling which used parameters for a stabilized surface also found high wind speeds to be an effective exogeneous disturbance capable of forming blowouts (Barchyn & Hugenholtz, 2013). Plausible parameters which could promote surface stabilization could be grain armoring (e.g., Blake et al., 2013; Weitz et al., 2018), surface cementation (Nickling, 1984), or fluctuations in near-surface wetness (Wiggs et al., 2004). Modeled storm events show that wind speed within a blowout after initiation will increase above the sediment carrying threshold and lead to erosion (Smyth et al., 2013). The extent of erosion strongly increases with higher wind velocities, showing a positive correlation between wind speed and erosional intensity (Smyth et al., 2019). We suggest that the observed scour-and-fill structures may have resulted from localized surface deflation due to the interplay between high-velocity, low sediment-saturation wind activity with a stabilized or partially stabilized surface. While the exact timescale for such processes on Mars remains uncertain, analogous blowout development on Earth typically occurs over decades (Abhar et al., 2015; Hugenholtz & Wolfe, 2006; Kayhko, 2007; Luo, Wang, Shao, et al., 2019) and even centuries (Luo, Wang, Lu, et al., 2019) suggesting a potentially similar timeframe under Martian conditions.

The stratigraphy prior to the scour-and-fill structures in the Mirador formation is dominated by aeolian deposition, characterized by sandsheets and aeolian dunes (Edgar et al., 2024; Gupta et al., 2022; Rapin et al., 2021; Roberts et al., 2024). The transition to an erosive regime marked by significant wind deflation suggests a shift in environmental conditions, likely driven by an increase in wind velocity and/or a decrease in wind sediment-saturation. These scour-and-fill structures have not been observed in the lower stratigraphy of the Mirador formation and are restricted to a single stratigraphic interval (−3,829 to −3,841 m), after which aeolian deposition in a sandsheet environment resumes again (Section 4; Roberts et al., 2023). This suggests that the conditions that formed the scours were constrained to a specific time interval. This naturally leads to the inference that the formation of the scour-and-fill features may represent an interval of sustained, higher-intensity wind conditions in Gale crater that led to episodes of aeolian deflation to form the scour surfaces.

8. Conclusions

This study documents decameter-wide, concave-up scour-and-fill structures in the Chenapau member of the Mirador formation—the stratigraphic section that forms part of the base of the orbitally defined Layered Sulfate-bearing unit—exposed in the lower foothills of Aeolis Mons, Gale crater. Detailed analysis of their geometries,

infill architecture, and associated facies reveals two distinct types of scour-and-fill structures, reflecting separate formative processes. The stratigraphy of the Chenapau member is interpreted as aeolian, characterized by planar, laterally extensive laminations with a pin-stripe pattern indicative of wind-ripple migration. The tabular nature, planar stratification, and lateral continuity of these deposits suggest deposition in a wind-transported sandsheet, where near-surface water inhibited dune formation. The two distinct types of scour-and-fill structures can be grouped into two classes: (A) broad, simple scours with a light-toned draping infill which reach up to ~60 m in width; and (B) small scours with lateral pinching and a dark-toned appearing infill. A singular scour that represents scour class B was identified in our research area. We interpret this class B scour as a fluvial scour that represents preserved channel wings and an infill comprised of cm-scale, tabular cross-stratification, which is characteristic of fluvial dunes. This scour represents a distinct episode of fluvial activity, unrelated to the processes responsible for class A. In contrast, the geometry of class A scour-and-fill structures—including broad and symmetrical cross-sectional concave profiles and flat central portions—and their overfilled, light-toned infill, continuous with the surrounding sandsheet stratigraphy, suggests they are aeolian in origin. More specifically, the geometry, architecture, and infill facies are consistent with blowout structures. These blowouts likely formed due to localized wind deflation of a stabilized surface, driven by increased wind velocity and/or decreased wind sediment saturation, developing over timescales of decades or even centuries. Class A scour-and-fill structures are concentrated within the same stratigraphic interval at similar elevations, suggesting a distinct, temporally confined transition from the environment and wind regime which deposited the underlying aeolian dunes and sandsheets in the Mirador formation, to one of heightened and sustained wind deflation. Collectively, the class A scours provide evidence for a regional event of higher wind velocity and deflation of an aeolian environment during the formation of Gale crater's Layered Sulfate-bearing unit, consistent with a long term trend of an aridifying paleoenvironment.

Acknowledgments

We would like to express our gratitude to the engineering, science, and management teams of the NASA Mars Science Laboratory (MSL) Project, whose efforts have made this research possible. Special thanks are extended to the many MSL team members who contributed to both tactical and strategic operations during the Marker Band valley campaign. We also particularly thank the Malin Space Science Systems operations team for their dedication in acquiring extensive image data and for generating the Mastcam mosaic products that were integral to this study. Additionally, we are grateful to Dave Rubin for his valuable contributions to the discussions. This work was supported by the Science and Technology Facilities Council (STFC), ST/W507520/1 (A. Roberts); the U.K. Space Agency, ST/Y000137/1, ST/S001506/1 (S.G. Banham); ST/X002373/1, ST/S001492/1 (S. Gupta); and ST/W002566/2 (J. Davis); and by the National Aeronautics and Space Administration (NASA), 80NSSC22K0731 (E. Kite), 80NSSC22K0779 (J. R. Johnson). The data presented in this research are archived with the NASA Planetary Data System (pds.nasa.gov) and can be accessed through the MSL Curiosity Analyst's Notebook (<https://an.rsl.wustl.edu/msl>). Portions of this research were conducted at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Finally, we would like to thank Benjamin Cardenas and Kathryn Stack Morgan for their insightful and constructive reviews, and the editors of *Journal of Geophysical Research: Planets* for coordinating the reviews and overall editorial process. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Data Availability Statement

The HiRISE mosaic used in this research is available through Calef and Parker (2016; https://astrogeology.usgs.gov/search/map/mars_msl_gale_merged_orthophoto_mosaic_25cm). Additional data from HiRISE (McEwen et al., 2007; <https://doi.org/10.1029/2005JE002605>) and CTX (Malin et al., 2007; <https://doi.org/10.1029/2006JE002808>) images can be accessed at the NASA Planetary Data System Geosciences Node (<https://pds-geosciences.wustl.edu/missions/mro/default.htm>). All Mastcam (Malin et al., 2017; <https://doi.org/10.1002/2016EA000252>) and MAHLI (Edgett et al., 2012; <https://doi.org/10.1007/s11214-012-9910-4>) images referenced in this manuscript can be found at the NASA Planetary Data System Cartography and Imaging Sciences Node (<https://pds-imaging.jpl.nasa.gov/volumes/msl.html>).

References

- Abhar, K. C., Walker, I. J., Hesp, P. A., & Gares, P. A. (2015). Spatial-temporal evolution of aeolian blowout dunes at Cape Cod. *Geomorphology*, 236, 148–162. <https://doi.org/10.1016/j.geomorph.2015.02.015>
- Abrantes, F. R., Basilici, G., & Soares, M. V. T. (2020). Mesoproterozoic erg and sand sheet system: Architecture and controlling factors (Galho do Miguel Formation, SE Brazil). *Precambrian Research*, 338, 105592. <https://doi.org/10.1016/j.precamres.2019.105592>
- Alexander, D. A., Deen, R. G., Andres, P. M., Zamani, P., Mortensen, H. B., Chen, A. C., et al. (2006). Processing of Mars Exploration Rover imagery for science and operations planning. *Journal of Geophysical Research*, 111(E2). <https://doi.org/10.1029/2005je002462>
- Allen, B. D., & Anderson, R. Y. (2000). A continuous, high-resolution record of late Pleistocene climate variability from the Estancia basin, New Mexico. *Geological Society of America Bulletin*, 112(9), 1444–1458. [https://doi.org/10.1130/0016-7606\(2000\)112<1444:achrrro>2.0.co;2](https://doi.org/10.1130/0016-7606(2000)112<1444:achrrro>2.0.co;2)
- Anderson, R., & Bell, J., III. (2010). Geologic mapping and characterization of Gale Crater and implications for its potential as a Mars Science Laboratory landing site. *Mars*, 5, 76–128. <https://doi.org/10.1555/mars.2010.0004>
- Anderson, W., & Day, M. (2017). Turbulent flow over craters on Mars: Vorticity dynamics reveal aeolian excavation mechanism. *Physical Review E*, 96(4), 043110. <https://doi.org/10.1103/physreve.96.043110>
- Baird, T. R., Bristow, C. S., Luo, W. Y., Du, E., Bryant, R. G., Mitchell, T. M., & Vermeesch, P. (2021). Blowout morphometrics and mass balances. *Frontiers in Earth Science*, 9. <https://doi.org/10.3389/feart.2021.669440>
- Banham, S. G., Gupta, S., Roberts, A., Davis, J., Cowart, A., Schieber, J., et al. (2024). Diagenesis is controlled by primary aeolian depositional processes in the Mirador formation (Gale crater, Mars). In *The 55th Lunar and Planetary Science Conference*.
- Banham, S. G., Roberts, A., Gupta, S., Davis, J., Thompson, C. K., Rubin, D., et al. (2024). Ice? Salt? Pressure? Sediment deformation structures as evidence of late-stage shallow ground water in Gale crater, Mars. *Geology*, 52(7), 492–496. <https://doi.org/10.1130/g51849.1>
- Banham, S. G., Gupta, S., Rubin, D. M., Bedford, C. C., Edgar, L. A., Bryk, A. B., et al. (2022). Evidence for fluctuating wind in shaping an ancient martian dune field: The Stimson formation at the Greenheugh Pediment, Gale Crater. *Journal of Geophysical Research-Planets*, 127(9). <https://doi.org/10.1029/2021je007023>
- Banham, S. G., Gupta, S., Rubin, D. M., Watkins, J. A., Sumner, D. Y., Edgett, K. S., et al. (2018). Ancient Martian aeolian processes and palaeomorphology reconstructed from the Stimson formation on the lower slope of Aeolis Mons, Gale crater, Mars. *Sedimentology*, 65(4), 993–1042. <https://doi.org/10.1111/sed.12469>

- Banham, S. G., & Mountney, N. P. (2014). Climatic versus halokinetic control on sedimentation in a dryland fluvial succession. *Sedimentology*, 61(2), 570–608. <https://doi.org/10.1111/sed.12064>
- Barchyn, T. E., & Hugenholtz, C. H. (2013). Reactivation of supply-limited dune fields from blowouts: A conceptual framework for state characterization. *Geomorphology*, 201, 172–182. <https://doi.org/10.1016/j.geomorph.2013.06.019>
- Bell, J. F., Godber, A., McNair, S., Caplinger, M. A., Maki, J. N., Lemmon, M. T., et al. (2017). The Mars Science Laboratory rover Mastcam instruments: Preflight and in-flight calibration, validation, and data archiving. *Earth and Space Science*, 4(7), 396–452. <https://doi.org/10.1002/2016ea000219>
- Besly, B., Romain, H. G., & Mountney, N. P. (2018). Reconstruction of linear dunes from ancient aeolian successions using subsurface data: Permian Auk Formation, Central North Sea, UK. *Marine and Petroleum Geology*, 91, 1–18. <https://doi.org/10.1016/j.marpetgeo.2017.12.021>
- Bibring, J. P., Langevin, Y., Mustard, J. F., Poulet, F., Arvidson, R., Gendrin, A., et al. (2006). Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. *Science*, 312(5772), 400–404. <https://doi.org/10.1126/science.1122659>
- Blake, D. F., Morris, R. V., Kocurek, G., Morrison, S. M., Downs, R. T., Bish, D., et al. (2013). Curiosity at Gale Crater, Mars: Characterization and analysis of the rocknest sand shadow. *Science*, 341, 6153. <https://doi.org/10.1126/science.1239505>
- Blakey, R. C. (1988). Superscoops—Their significance as elements of eolian architecture. *Geology*, 16(6), 483–487. [https://doi.org/10.1130/0091-7613\(1988\)016<0483:stsao>2.3.co;2](https://doi.org/10.1130/0091-7613(1988)016<0483:stsao>2.3.co;2)
- Buffington, J. M., & Montgomery, D. R. (2022). Geomorphic classification of rivers: An updated review. In J. F. Shroder (Ed.), *Treatise on geomorphology* (pp. 1143–1190). Academic Press.
- Cain, S. A., & Mountney, N. P. (2009). Spatial and temporal evolution of a terminal fluvial fan system: The Permian Organ Rock Formation, South-east Utah, USA. *Sedimentology*, 56(6), 1774–1800. <https://doi.org/10.1111/j.1365-3091.2009.01057.x>
- Calef, F., & Parker, T. (2016). MSL gale merged orthophoto mosaic: PDS Annex. *U.S. Geological Survey*.
- Caravaca, G., Le Mouélic, S., Gupta, S., Mangold, N., Rapin, W., Schieber, J., et al. (2022). The Prow outcrop: An “open catalog” of multiscale 3D fluvial sedimentary structures in the lower sulfate unit of Gale crater (Mars). In *Proceedings Europlanet Science Congress*.
- Caravaca, G., Mangold, N., Dehouck, E., Schieber, J., Zaugg, L., Bryk, A. B., et al. (2022). From lake to river: Documenting an environmental transition across the Jura/Knockfarril hill members boundary in the Glen Torridon region of Gale Crater (Mars). *Journal of Geophysical Research-Planets*, 127(9). <https://doi.org/10.1029/2021je007093>
- Cardenas, B. T., Grotzinger, J. P., Lamb, M. P., Lewis, K. W., Fedo, C. M., Bryk, A. B., et al. (2022). Barform deposits of the Carolyn Shoemaker formation, Gale Crater, Mars. *Journal of Sedimentary Research*, 92(12), 1071–1092. <https://doi.org/10.2110/jsr.2022.032>
- Cardenas, B. T., Kocurek, G., Mohrig, D., Swanson, T., Hughes, C. M., & Brothers, S. C. (2019). Preservation of autogenic processes and allogenic forcings in set-scale aeolian architecture II: The scour-and-fill dominated Jurassic Page Sandstone, Arizona, USA. *Journal of Sedimentary Research*, 89(8), 741–760. <https://doi.org/10.2110/jsr.2019.41>
- Carr, M. H., & Head, J. W. (2010). Geologic history of Mars. *Earth and Planetary Science Letters*, 294(3–4), 185–203. <https://doi.org/10.1016/j.epsl.2009.06.042>
- Chakraborty, T., & Chakraborty, C. (2001). Eolian-aqueous interactions in the development of a proterozoic sand sheet: Shikhaoda Formation, Hosangabad, India. *Journal of Sedimentary Research*, 71(1), 107–117. <https://doi.org/10.1306/031700710107>
- Chandler, M. A., Kocurek, G., Goggin, D. J., & Lake, L. W. (1989). Effects of stratigraphic heterogeneity on permeability in eolian sandstone sequence, Page Sandstone, Northern Arizona. *AAPG Bulletin*, 73(5), 658–668. <https://doi.org/10.1306/44b4a249-170a-11d7-8645000102c1865d>
- Charlton, R. (2007). *Fundamentals of fluvial geomorphology*. Routledge.
- Day, M., & Kocurek, G. (2016). Observations of an aeolian landscape: From surface to orbit in Gale Crater. *Icarus*, 280, 37–71. <https://doi.org/10.1016/j.icarus.2015.09.042>
- Dickson, J. L., Kerber, L. A., Fassett, C. I., & Ehlmann, B. L. (2018). A global, blended CTX mosaic of Mars with vectorized seam mapping: A new mosaicking pipeline using principles of non-destructive image editing. In *The 49th Lunar and Planetary Science Conference*.
- Dromart, G., Le Deit, L., Rapin, W., Gasnault, O., Le Mouélic, S., Quantin-Nataf, C., et al. (2021). Deposition and erosion of a light-toned Yardang-forming unit of Mt Sharp, Gale crater, Mars. *Earth and Planetary Science Letters*, 554, 116681. <https://doi.org/10.1016/j.epsl.2020.116681>
- Edgar, L. A., Fedo, C. M., Gupta, S., Banham, S. G., Fraeman, A. A., Grotzinger, J. P., et al. (2020). A lacustrine paleoenvironment recorded at Vera Rubin Ridge, Gale Crater: Overview of the sedimentology and stratigraphy observed by the Mars science laboratory curiosity rover. *Journal of Geophysical Research-Planets*, 125(3). <https://doi.org/10.1029/2019je006307>
- Edgar, L. A., Grotzinger, J., Fedo, C. M., Meyer, M., Rapin, W., Dietrich, W. E., et al. (2024). Wet to dry depositional environments recorded in the clay-sulfate transition region in Gale Crater, Mars: Overview and stratigraphic context for Curiosity's exploration campaign. In *55th Lunar Planetary Science Conference*.
- Edgett, K. S., Caplinger, M. A., Maki, J. N., Ravine, M. A., Ghaemi, F. T., McNair, S., et al. (2015). Curiosity's robotic arm-mounted Mars hand lens imager (MAHLI): Characterization and calibration status: MSL mahli technical report.
- Edgett, K. S., & Sarkar, R. (2021). Recognition of sedimentary rock occurrences in satellite and aerial images of other worlds-insights from Mars. *Remote Sensing*, 13(21), 4296. <https://doi.org/10.3390/rs13214296>
- Edgett, K. S., Yingst, R. A., Ravine, M. A., Caplinger, M. A., Maki, J. N., Ghaemi, F. T., et al. (2012). Curiosity's mars hand lens imager (MAHLI) investigation. *Space Science Reviews*, 170(1–4), 259–317. <https://doi.org/10.1007/s11214-012-9910-4>
- Engel, F. L., & Rhoads, B. L. (2012). Interaction among mean flow, turbulence, bed morphology, bank failures and channel planform in an evolving compound meander loop. *Geomorphology*, 163, 70–83. <https://doi.org/10.1016/j.geomorph.2011.05.026>
- Fedo, C. M., Bryk, A. B., Edgar, L. A., Bennett, K. A., Fox, V. K., Dietrich, W. E., et al. (2022). Geology and stratigraphic correlation of the Murray and Carolyn Shoemaker formations across the Glen Torridon Region, Gale Crater, Mars. *Journal of Geophysical Research-Planets*, 127(9). <https://doi.org/10.1029/2022je007408>
- Ferronato, J. P. F., Scherer, C. M. D., de Souza, E. G., dos Reis, A. D., & de Mello, R. G. (2019). Genetic units and facies architecture of a Lower Cretaceous fluvial-aeolian succession, Sao Sebastiao formation, Jatoba basin, Brazil. *Journal of South American Earth Sciences*, 89, 158–172. <https://doi.org/10.1016/j.jsames.2018.11.009>
- Fraeman, A. A., Ehlmann, B. L., Arvidson, R. E., Edwards, C. S., Grotzinger, J. P., Milliken, R. E., et al. (2016). The stratigraphy and evolution of lower Mount Sharp from spectral, morphological, and thermophysical orbital data sets. *Journal of Geophysical Research: Planets*, 121(9), 1713–1736. <https://doi.org/10.1002/2016je005095>
- Fryberger, S. G., Ahlbrandt, T. S., & Andrews, S. (1979). Origin, sedimentary features, and significance of low-angle eolian sand sheet deposits, Great Sand Dunes National Monument and Vicinity, Colorado. *Journal of Sedimentary Petrology*, 49(3), 733–746. <https://doi.org/10.1306/212f782e-2b24-11d7-8648000102c1865d>

- Fryberger, S. G., & Schenk, C. J. (1988). Pin stripe lamination—A distinctive feature of modern and ancient eolian sediments. *Sedimentary Geology*, 55(1–2), 1–15. [https://doi.org/10.1016/0037-0738\(88\)90087-5](https://doi.org/10.1016/0037-0738(88)90087-5)
- Gibling, M. R. (2006). Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification. *Journal of Sedimentary Research*, 76(5–6), 731–770. <https://doi.org/10.2110/jsr.2006.060>
- Goudie, A. (2023). *Dunes, desert landscapes of the World with Google Earth*. Springer.
- Gradzinski, R. (1992). Deep blowout depressions in the aeolian Tumlin Sandstone (Lower Triassic) of the Holy-Cross Mountains, Central Poland. *Sedimentary Geology*, 81(3–4), 231–242. [https://doi.org/10.1016/0037-0738\(92\)90072-y](https://doi.org/10.1016/0037-0738(92)90072-y)
- Grant, J. A., Wilson, S. A., Mangold, N., Calef, F., & Grotzinger, J. P. (2014). The timing of alluvial activity in Gale crater, Mars. *Geophysical Research Letters*, 41(4), 1142–1148. <https://doi.org/10.1002/2013gl058909>
- Grotzinger, J. P., Arvidson, R. E., Bell, J. F., Calvin, W., Clark, B. C., Fike, D. A., et al. (2005). Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters*, 240(1), 11–72. <https://doi.org/10.1016/j.epsl.2005.09.039>
- Grotzinger, J. P., Gupta, S., Malin, M., Rubin, D., Schieber, J., Siebach, K., et al. (2015). Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. *Science*, 350, 6257. <https://doi.org/10.1126/science.aac7575>
- Grotzinger, J. P., Sumner, D. Y., Kah, L. C., Stack, K., Gupta, S., Edgar, L., et al. (2014). A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. *Science*, 343, 6169. <https://doi.org/10.1126/science.1242777>
- Gupta, S., Dietrich, W., Lewis, K., Mondro, C. A., Kite, E. S., Weitz, C. M., et al. (2023). Rippled to bits: Tales of transient lakes in a martian desert. In *AGU Fall Meeting 2023*.
- Gupta, S., Dietrich, W. E., Lewis, K., Kite, E. S., Mondro, C. A., Schieber, J., et al. (2023). High' but not so dry on Aeolis Mons. In *The 54th Lunar and Planetary Science Conference*.
- Gupta, S., Edgar, L., Yingst, R., Bryk, A., Caravaca, G., Dietrich, W., et al. (2022). Episodic aqueous conditions punctuated dominantly aeolian deposition within the layered sulphate-bearing unit, Gale crater (Mars). In *Proceedings Europlanet Science Congress* (p. 963).
- Gwizd, S., Fedo, C., Grotzinger, J., Banham, S., Rivera-Hernández, F., Gupta, S., et al. (2024). Evolution of a lake margin recorded in the Sutton Island member of the Murray Formation, Gale Crater, Mars. *Journal of Geophysical Research-Planets*, 129(1). <https://doi.org/10.1029/2023je007919>
- Hasiotis, S. T., Chan, M. A., & Parrish, J. T. (2021). Defining bounding surfaces within and between eolian and non-eolian deposits, lower Jurassic Navajo Sandstone, Moab area, Utah, USA: Implications for subdividing Erg system strata. *Journal of Sedimentary Research*, 91(12), 1275–1304. <https://doi.org/10.2110/jsr.2021.027>
- Havholm, K. G., & Kocurek, G. (1994). Factors controlling aeolian sequence stratigraphy: Clues from super bounding surface features in the middle Jurassic page sandstone. *Sedimentology*, 41(5), 913–934. <https://doi.org/10.1111/j.1365-3091.1994.tb01432.x>
- Heme de Lacotte, V. J. P., & Mountney, N. P. (2022). A classification scheme for sedimentary architectures arising from aeolian-fluvial system interactions: Permian examples from southeast Utah, USA. *Aeolian Research*, v. 58, 100815. <https://doi.org/10.1016/j.aeolia.2022.100815>
- Hesp, P. A. (1996). Flow dynamics in a trough blowout. *Boundary-Layer Meteorology*, 77(3–4), 305–330. <https://doi.org/10.1007/bf00123530>
- Hesp, P. A. (2002). Foredunes and blowouts: Initiation, geomorphology and dynamics. *Geomorphology*, 48(1–3), 245–268. [https://doi.org/10.1016/S0169-555X\(02\)00184-8](https://doi.org/10.1016/S0169-555X(02)00184-8)
- Hesp, P. A., Hilton, M., & Konlecher, T. (2017). Flow and sediment transport dynamics in a slot and cauldron blowout and over a foredune, Mason Bay, Stewart Island (Rakiura), NZ. *Geomorphology*, 295, 598–610. <https://doi.org/10.1016/j.geomorph.2017.08.024>
- Hesp, P. A., & Hyde, R. (1996). Flow dynamics and geomorphology of a trough blowout. *Sedimentology*, 43(3), 505–525. <https://doi.org/10.1046/j.1365-3091.1996.d01-22.x>
- Hesp, P. A., & Walker, I. J. (2012). Three-dimensional aeolian dynamics within a bowl blowout during offshore winds: Greenwich Dunes, Prince Edward Island, Canada. *Aeolian Research*, 3(4), 389–399. <https://doi.org/10.1016/j.aeolia.2011.09.002>
- Hesp, P. A., & Walker, I. J. (2013). Aeolian geomorphology, Treatise on geomorphology.
- Hugenholtz, C. H., & Wolfe, S. A. (2006). Morphodynamics and climate controls of two aeolian blowouts on the northern Great Plains, Canada. *Earth Surface Processes and Landforms*, 31(12), 1540–1557. <https://doi.org/10.1002/esp.1367>
- Hugenholtz, C. H., & Wolfe, S. A. (2009). Form-flow interactions of an aeolian saucer blowout. *Earth Surface Processes and Landforms*, 34(7), 919–928. <https://doi.org/10.1002/esp.1776>
- Hugenholtz, C. H., Wolfe, S. A., & Moorman, B. J. (2007). Sand-water flows on cold-climate eolian dunes: Environmental analogs for the eolian rock record and martian sand dunes. *Journal of Sedimentary Research*, 77(7–8), 607–614. <https://doi.org/10.2110/jsr.2007.063>
- Hunter, R. E. (1977). Basic types of stratification in small eolian dunes. *Sedimentology*, 24(3), 361–387. <https://doi.org/10.1111/j.1365-3091.1977.tb00128.x>
- Jaeger, K. L., Sutfin, N. A., Tooth, S., Michaelides, K., & Singer, M. (2017). 2.1 geomorphology and sediment regimes of intermittent rivers and ephemeral streams. In *Intermittent rivers and ephemeral streams*.
- Jewell, M., Houser, C., & Trimble, S. (2017). Phases of blowout initiation and stabilization on Padre Island revealed through ground-penetrating radar and remotely sensed imagery. *Physical Geography*, 38(6), 556–577. <https://doi.org/10.1080/02723646.2017.1338042>
- Kayhko, J. (2007). Aeolian blowout dynamics in subarctic Lapland based on decadal levelling investigations. *Geografiska Annaler - Series A: Physical Geography*, 89a(1), 65–81. <https://doi.org/10.1111/j.1468-0459.2007.00308.x>
- Kite, E. S., Lewis, K. W., Lamb, M. P., Newman, C. E., & Richardson, M. I. (2013). Growth and form of the mound in Gale Crater, Mars: Slope wind enhanced erosion and transport. *Geology*, 41(5), 543–546. <https://doi.org/10.1130/g33909.1>
- Kocurek, G., & Day, M. (2018). What is preserved in the aeolian rock record? A Jurassic Entrada sandstone case study at the Utah-Arizona border. *Sedimentology*, 65(4), 1301–1321. <https://doi.org/10.1111/sed.12422>
- Kocurek, G., & Havholm, K. G. (1993). Eolian sequence stratigraphy—A conceptual framework: Chapter 16: Recent developments in siliciclastic sequence stratigraphy, siliciclastic sequence stratigraphy: Recent developments and applications (pp. 393–409).
- Kocurek, G., & Nielson, J. (1986). Conditions favorable for the formation of warm-climate aeolian sand sheets. *Sedimentology*, 33(6), 795–816. <https://doi.org/10.1111/j.1365-3091.1986.tb00983.x>
- Kocurek, G., Robinson, N. I., & Sharp, J. M. (2001). The response of the water table in coastal aeolian systems to changes in sea level. *Sedimentary Geology*, 139(1), 1–13. [https://doi.org/10.1016/S0037-0738\(00\)00137-8](https://doi.org/10.1016/S0037-0738(00)00137-8)
- Langford, R. P., & Chan, M. A. (1989). Fluvial-aeolian interactions. 2. Ancient systems. *Sedimentology*, 36(6), 1037–1051. <https://doi.org/10.1111/j.1365-3091.1989.tb01541.x>
- Le Deit, L., Hauber, E., Fueten, F., Pondrelli, M., Rossi, A. P., & Jaumann, R. (2013). Sequence of infilling events in Gale Crater, Mars: Results from morphology, stratigraphy, and mineralogy. *Journal of Geophysical Research-Planets*, 118(12), 2439–2473. <https://doi.org/10.1002/2012je004322>

- Le Mouelic, S., Gasnault, O., Herkenhoff, K., Bridges, N., Langevin, Y., Mangold, N., et al. (2015). The ChemCam remote micro-imager at Gale crater: Review of the first year of operations on Mars. *Icarus*, 249, 93–107. <https://doi.org/10.1016/j.icarus.2014.05.030>
- Le Mouelic, S., Gasnault, O., Herkenhoff, K., Newsom, H., Gallegos, Z., Rapin, W., et al. (2019). Correction of Stray light in CHEMCAM remote micro-imager long distance images. In *The 50th Lunar and Planetary Science Conference*.
- Levin, N. (2011). Climate-driven changes in tropical cyclone intensity shape dune activity on Earth's largest sand island. *Geomorphology*, 125(1), 239–252. <https://doi.org/10.1016/j.geomorph.2010.09.021>
- Luo, W. Y., Wang, Z. Y., Lu, J. F., Yang, L. H., Qian, G. Q., Dong, Z. B., & Bateman, M. D. (2019). Mega-blowouts in Qinghai-Tibet Plateau: Morphology, distribution and initiation. *Earth Surface Processes and Landforms*, 44(2), 449–458. <https://doi.org/10.1002/esp.4507>
- Luo, W. Y., Wang, Z. Y., Shao, M., Lu, J. F., Qian, G. Q., Dong, Z. B., et al. (2019). Historical evolution and controls on mega-blowouts in northeastern Qinghai-Tibetan Plateau, China. *Geomorphology*, 329, 17–31. <https://doi.org/10.1016/j.geomorph.2018.12.033>
- Maki, J. (2018). In N. P. D. System (Ed.), *MSL Mars navigation Camera 5 RDR V2.0*.
- Maki, J., Thiessen, D., Pourangi, A., Kobzeff, P., Litwin, T., Scherr, L., et al. (2012). The Mars science laboratory engineering cameras. *Space Science Reviews*, 170(1–4), 77–93. https://doi.org/10.1007/978-1-4614-6339-9_5
- Malin, M. C., Bell, J. F., Cantor, B. A., Caplinger, M. A., Calvin, W. M., Clancy, R. T., et al. (2007). Context camera investigation on board the Mars reconnaissance orbiter. *Journal of Geophysical Research*, 112(E5). <https://doi.org/10.1029/2006je002808>
- Malin, M. C., & Edgett, K. S. (2000). Sedimentary rocks of early Mars. *Science*, 290(5498), 1927–1937. <https://doi.org/10.1126/science.290.5498.1927>
- Malin, M. C., Ravine, M. A., Caplinger, M. A., Ghaemi, F. T., Schaffner, J. A., Maki, J. N., et al. (2017). The Mars science laboratory (MSL) mast cameras and descent imager: Investigation and instrument descriptions. *Earth and Space Science*, 4(8), 506–539. <https://doi.org/10.1002/2016ea000252>
- McEwen, A. S., Eliason, E. M., Bergstrom, J. W., Bridges, N. T., Hansen, C. J., Delamere, W. A., et al. (2007). Mars reconnaissance orbiter's high resolution imaging science experiment (HiRISE). *Journal of Geophysical Research*, 112, E5. <https://doi.org/10.1029/2005je002605>
- Mesquita, A. F., Basilici, G., Soares, M. V. T., Janocko, J., Mountney, N. P., Colombero, L., & de Souza, C. R. (2021). Hybrid dry-wet interdune deposition in Precambrian aeolian systems: Galho do Miguel Formation, SE Brazil. *Sedimentary Geology*, 425, 106007.
- Milliken, R. E., Ewing, R. C., Fischer, W. W., & Hurowitz, J. (2014). Wind-blown sandstones cemented by sulfate and clay minerals in Gale Crater, Mars. *Geophysical Research Letters*, 41(4), 1149–1154. <https://doi.org/10.1002/2013gl059097>
- Milliken, R. E., Grotzinger, J. P., & Thomson, B. J. (2010). Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater. *Geophysical Research Letters*, 37(4). <https://doi.org/10.1029/2009gl041870>
- Mondro, C. A., Grotzinger, J., Fedo, C. M., Lamb, M. P., Gupta, S., Dietrich, W. E., et al. (2025). Depositional environment of the Amapari marker band: Rising water levels formed kilometer-scale lake in Gale Crater, Mars. *Journal of Geophysical Research: Planets*, 130(3). <https://doi.org/10.1029/2024je008606>
- Mountney, N. P. (2006a). Eolian facies models. In H. W. Posamentier & R. G. Walker (Eds.), *Facies models revisited*. SEPM Society for Sedimentary Geology.
- Mountney, N. P. (2006b). Periodic accumulation and destruction of aeolian erg sequences in the Permian Cedar Mesa Sandstone, White Canyon, southern Utah, USA. *Sedimentology*, 53(4), 789–823.
- Mountney, N. P., & Thompson, D. B. (2002). Stratigraphic evolution and preservation of aeolian dune and damp/wet interdune strata: An example from the Triassic Helsby Sandstone Formation, Cheshire Basin, UK. *Sedimentology*, 49(4), 805–833. <https://doi.org/10.1046/j.1365-3091.2002.00472.x>
- Neal, A., & Roberts, C. L. (2001). Internal structure of a trough blowout, determined from migrated ground-penetrating radar profiles. *Sedimentology*, 48(4), 791–810. <https://doi.org/10.1046/j.1365-3091.2001.00382.x>
- Nickling, W. G. (1984). The stabilizing role of bonding agents on the entrainment of sediment by wind. *Sedimentology*, 31(1), 111–117. <https://doi.org/10.1111/j.1365-3091.1984.tb00726.x>
- Pedersen, K., & Clemmensen, L. B. (2005). Unveiling past aeolian landscapes: A ground-penetrating radar survey of a Holocene coastal dunefield system, Thy, Denmark (vol 177, pg 57, 2005). *Sedimentary Geology*, 181(3–4), 231–233. <https://doi.org/10.1016/j.sedgeo.2005.08.002>
- Priddy, C. L., & Clarke, S. M. (2020). The sedimentology of an ephemeral fluvial-aeolian succession. *Sedimentology*, 67(5), 2392–2425. <https://doi.org/10.1111/sed.12706>
- Prosser, D. J., & Maskall, R. (1993). Permeability variation within aeolian sandstone: A case study using core cut sub-parallel to slipface bedding, the Auk Field, Central North Sea. *Geological Society, London, Special Publications*, 73(1), 377–397. <https://doi.org/10.1144/gsl.sp.1993.073.01.22>
- Ramirez, R. M., & Craddock, R. A. (2018). The geological and climatological case for a warmer and wetter early Mars. *Nature Geoscience*, 11(4), 230–237. <https://doi.org/10.1038/s41561-018-0093-9>
- Rapin, W., Dromart, G., Rubin, D., Le Deit, L., Mangold, N., Edgar, L. A., et al. (2021). Alternating wet and dry depositional environments recorded in the stratigraphy of Mount Sharp at Gale crater, Mars: Geology. *Geology*, 49(7), 842–846. <https://doi.org/10.1130/g48519.1>
- Rapin, W., Dromart, G., Schieber, J., Clark, A. H., Kah, L. C., Rubin, D., et al. (2023). *Aridification sequence and formation of sulfates in Aeolis Mons, Gale crater, FAIRPLAY Workshop*. European Space Research and Technology Centre.
- Rivera-Hernández, F., Sumner, D. Y., Mangold, N., Stack, K. M., Forni, O., Newsom, H., et al. (2019). Using ChemCam LIBS data to constrain grain size in rocks on Mars: Proof of concept and application to rocks at Yellowknife Bay and Pahrump Hills, Gale crater. *Icarus*, 321, 82–98. <https://doi.org/10.1016/j.icarus.2018.10.023>
- Roberts, A. L., Gupta, S., Cowart, A., Edgar, L., Dietrich, W. E., Rapin, W., et al. (2024). Depositional processes and environments of the layered sulfate-bearing unit, Gale crater, Mars. In *Proceedings Tenth International Conference on Mars 2024* (p. 3515).
- Roberts, A. L., Gupta, S., Dietrich, W. E., Edgar, L., Rapin, W., Banham, S., et al. (2023). What Depositional Processes and Palaeoenvironments Formed the Layered Sulfate Unit in Gale Crater, Mars. In *The 54th Lunar and Planetary Science Conference*.
- Rubin, D. M., & Hunter, R. E. (1982). Bedform climbing in theory and nature. *Sedimentology*, 29(1), 121–138. <https://doi.org/10.1111/j.1365-3091.1982.tb01714.x>
- Scherer, C. M., & Lavina, E. L. C. (2005). Sedimentary cycles and facies architecture of aeolian-fluvial strata of the Upper Jurassic Guar4 Formation, southern Brazil. *Sedimentology*, 52(6), 1323–1341. <https://doi.org/10.1111/j.1365-3091.2005.00746.x>
- Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH image to ImageJ: 25 years of image analysis. *Nature Methods*, 9(7), 671–675. <https://doi.org/10.1038/nmeth.2089>
- Sheppard, R. Y., Thorpe, M. T., Fraeman, A. A., Fox, V. K., & Milliken, R. E. (2021). Merging perspectives on secondary minerals on Mars: A review of ancient water-rock interactions in Gale Crater inferred from orbital and in-situ observations. *Minerals*, 11(9), 986. <https://doi.org/10.3390/min11090986>

- Smith, A., Gares, P. A., Wasklewicz, T., Hesp, P. A., & Walker, I. J. (2017). Three years of morphologic changes at a bowl blowout, Cape Cod, USA. *Geomorphology*, 295, 452–466. <https://doi.org/10.1016/j.geomorph.2017.07.012>
- Smith, D. E., Zuber, M. T., Frey, H. V., Garvin, J. B., Head, J. W., Muhleman, D. O., et al. (2001). Mars orbiter laser altimeter: Experiment summary after the first year of global mapping of Mars. *Journal of Geophysical Research*, 106(E10), 23689–23722. <https://doi.org/10.1029/2000je001364>
- Smyth, T. A. G., Hesp, P. A., Walker, I. J., Wasklewicz, T., Gares, P. A., & Smith, A. B. (2019). Topographic change and numerically modelled near surface wind flow in a bowl blowout. *Earth Surface Processes and Landforms*, 44(10), 1988–1999. <https://doi.org/10.1002/esp.4625>
- Smyth, T. A. G., Jackson, D. W. T., & Cooper, J. A. G. (2013). Three dimensional airflow patterns within a coastal trough-bowl blowout during fresh breeze to hurricane force winds. *Aeolian Research*, 9, 111–123. <https://doi.org/10.1016/j.aeolia.2013.03.002>
- Stack, K. M., Grotzinger, J. P., Lamb, M. P., Gupta, S., Rubin, D. M., Kah, L. C., et al. (2019). Evidence for plunging river plume deposits in the Pahrump Hills member of the Murray formation, Gale crater, Mars. *Sedimentology*, 66(5), 1768–1802. <https://doi.org/10.1111/sed.12558>
- Swanson, T., Mohrig, D., Kocurek, G., Cardenas, B. T., & Wolinsky, M. A. (2019). Preservation of autogenic processes and allogenic forcings in set-scale aeolian architecture I: Numerical Experiments. *Journal of Sedimentary Research*, 89(8), 728–740. <https://doi.org/10.2110/jsr.2019.42>
- Taggart, S., Hampson, G. J., & Jackson, M. D. (2010). High-resolution stratigraphic architecture and lithological heterogeneity within marginal aeolian reservoir analogues. *Sedimentology*, 57(5), 1246–1279. <https://doi.org/10.1111/j.1365-3091.2010.01145.x>
- Tanaka, K. L., Robbins, S. J., Fortezzo, C. M., Skinner, J. A., & Hare, T. M. (2014). The digital global geologic map of Mars: Chronostratigraphic ages, topographic and crater morphologic characteristics, and updated resurfacing history. *Planetary and Space Science*, 95, 11–24. <https://doi.org/10.1016/j.pss.2013.03.006>
- Thompson, L. M., Spray, J. G., VanBommel, S. J., O'Connell-Cooper, C. D., Berger, J. A., Gellert, R., et al. (2024). Amapari marker band, gale crater, Mars: Event horizon with highest bedrock iron and zinc concentrations detected by curiosity's alpha particle X-ray spectrometer. *Geophysical Research Letters*, 51(23), e2024GL111113. <https://doi.org/10.1029/2024gl111113>
- Thomson, B. J., Bridges, N. T., Milliken, R., Baldrige, A., Hook, S. J., Crowley, J. K., et al. (2011). Constraints on the origin and evolution of the layered mound in Gale Crater, Mars using Mars Reconnaissance Orbiter data. *Icarus*, 214(2), 413–432. <https://doi.org/10.1016/j.icarus.2011.05.002>
- Thornbury, W. D. (1954). *Principles of geomorphology*. John Wiley & Sons.
- Vasavada, A. R. (2022). Mission overview and scientific contributions from the Mars science laboratory curiosity rover after eight years of surface operations. *Space Science Reviews*, 218(3), 14. <https://doi.org/10.1007/s11214-022-00882-7>
- Vasavada, A. R., Grotzinger, J. P., Arvidson, R. E., Calef, F. J., Crisp, J. A., Gupta, S., et al. (2014). Overview of the Mars science Laboratory mission: Bradbury landing to Yellowknife Bay and beyond. *Journal of Geophysical Research-Planets*, 119(6), 1134–1161. <https://doi.org/10.1002/2014je004622>
- Warner, A. L., Hesp, P. A., Keane, R., & Gontz, A. M. (2022). Ground penetrating radar of Paleoblowouts and Transgressive Dunes, Young-husband Peninsula, South Australia. *Journal of Coastal Research*, 38(5). <https://doi.org/10.2112/jcoastres-d-20-00107.1>
- Watkins, J. A., Grotzinger, J. P., Stein, N. T., Banham, S. G., Gupta, S., Rubin, D. M., et al. (2022). Burial and exhumation of sedimentary rocks revealed by the base Stimson erosional Unconformity, Gale Crater, Mars. *Journal of Geophysical Research-Planets*, 127(7). <https://doi.org/10.1029/2022je007293>
- Weitz, C. M., Lewis, K., Kite, E. S., Dietrich, W. E., Thompson, L. M., O'connell-cooper, C., et al. (2023). The Marker Band in Gale crater. In *The 54th Lunar and Planetary Science Conference*.
- Weitz, C. M., Lewis, K. W., Bishop, J. L., Thomson, B. J., Arvidson, R. E., Grant, J. A., et al. (2022). Orbital observations of a marker horizon at Gale Crater. *Journal of Geophysical Research: Planets*, 127(4). <https://doi.org/10.1029/2022je007211>
- Weitz, C. M., Sullivan, R. J., Lapotre, M. G. A., Rowland, S. K., Grant, J. A., Baker, M., & Yingst, R. A. (2018). Sand grain sizes and shapes in eolian bedforms at Gale Crater, Mars. *Geophysical Research Letters*, 45(18), 9471–9479. <https://doi.org/10.1029/2018gl078972>
- Wiens, R. C., Maurice, S., Barraclough, B., Saccoccio, M., Barkley, W. C., Bell, J. F., et al. (2012). The ChemCam instrument suite on the Mars science laboratory (MSL) rover: Body unit and combined system tests. *Space Science Reviews*, 170(1–4), 167–227. <https://doi.org/10.1007/s11214-012-9902-4>
- Wiggs, G. F. S., Baird, A. J., & Atherton, R. J. (2004). The dynamic effects of moisture on the entrainment and transport of sand by wind. *Geomorphology*, 59(1–4), 13–30. <https://doi.org/10.1016/j.geomorph.2003.09.002>
- Williams, R. M. E., Grotzinger, J. P., Dietrich, W. E., Gupta, S., Sumner, D. Y., Wiens, R. C., et al. (2013). Martian fluvial conglomerates at Gale Crater. *Science*, 340(6136), 1068–1072. <https://doi.org/10.1126/science.1237317>
- Wohl, E. E. (1998). Bedrock channel morphology in relation to erosional processes, rivers over rock: Fluvial processes in bedrock channels (pp. 133–151).
- Yingst, R. A., Edgett, K. S., Kennedy, M. R., Krezoski, G. M., McBride, M. J., Minitti, M. E., et al. (2016). MAHLI on Mars: Lessons learned operating a geoscience camera on a landed payload robotic arm: Geoscientific Instrumentation methods and data. *Systems*, 5(1), 205–217. <https://doi.org/10.5194/gi-5-205-2016>