

Key Points:

- Strata at the Naukluft plateau records northward migrating aeolian compound dunes, which is consistent with the broader Stimson formation
- The stratigraphy is interpreted to represent the central section of the erg, which correlates with the sedimentary architecture observed at the Murray buttes
- Ground water resulted in the formation of concretions at the base of the formation, indicating a perched aquifer on top of the Murray formation

Supporting Information:

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

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Sedimentary Architecture of the Stimson Formation at the Naukluft Plateau, Gale Crater, Mars

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Abstract Sedimentary texture, facies, and architecture can be used to reconstruct the palaeoenvironment under which sediments accumulate. On Mars, palaeoenvironmental reconstructions are used to understand ancient Martian atmospheric circulation, surface sedimentary processes, and the presence of water, to provide insight into ancient habitability and climate evolution. Exploration of the Stimson formation at the Naukluft plateau, Gale crater, by the MSL rover Curiosity yielded evidence of aeolian dunes recorded within the strata, and that the Stimson formation unconformably overlies the older, lacustrine Murray formation. Analysis of the strata revealed a hierarchy of bounding surfaces forming compound cross-bedding, indicating two scales of bedform: primary dunes (draa) and superimposed dunes. Cross-set dip-azimuths indicate a broad sediment transport direction toward the north, aligning with the north or north-east transport direction of previous work. Paired with textural analysis, the outcrops of the Naukluft plateau are interpreted to have formed within the central section of a large, dry aeolian dune field. The formation of concretions, veins and alteration halos, formed by diagenesis or fracturing associated with sub-surface fluids, coincide with the lithification of the Stimson formation. This hints toward an extended presence of water within Gale crater but at a much lower abundance than earlier during the crater fill sequence. The unconformity denotes a large climatic transition from the lacustrine Murray formation to dry aeolian Stimson formation, reflecting long-term drying of the ancient environment. Such observations enhance the understanding of the ancient Martian environment, allowing reconstructions of atmospheric conditions, climate and habitability on a regional scale.

Plain Language Summary Wind transported sediments accumulate to form rocks which preserve a record of ancient surface conditions. By observing these rocks, a view of said conditions can be assembled, providing information about the ancient climate, variations in atmospheric circulation, and the presence and persistence of water. Additionally, after sediments are deposited and then buried, water within the subsurface can further modify the accumulated sediment. This study focuses on the Stimson formation at the Naukluft plateau (Gale crater), to understand the sedimentary processes which deposited the rocks that form the plateau. Analysis shows that the Stimson formation here is composed of compound cross-sets, which are the preserved expression of compound wind-driven sand dunes. Textural analysis confirms that the sediment transport mechanism was by aeolian processes, in common with the rest of the Stimson formation. After deposition, the basal part of the Stimson formation was saturated with water (immediately above the basal unconformity), permitting the growth of concretions. The presence of concretions at the base of the Stimson formation indicates that there was still groundwater present in Gale crater after the exhumation of Mount Sharp, during the drying out of the Martian surface during the Hesperian period, 3.7–3.0 Ga.

1. Introduction

Searching for habitable environments is foundational to many surface missions to Mars (MEPAG, 2020). The Mars Science Laboratory (MSL) mission rover Curiosity is exploring the stratigraphy of Gale crater to reconstruct palaeoenvironments and to search for ancient habitable environments (Grotzinger, Crisp, et al., 2015). The ongoing mission focus of characterizing sedimentary material is fundamental; it records the depositional and diagenetic information crucial to understanding past environments in preserved strata, along with any evidence of biosignatures (Sun et al., 2019). Sedimentary rocks encountered along the MSL rovers's traverse have been interpreted to build a picture of Martian climate history, based on the application of Earth-borne knowledge.

The MSL team have investigated rocks interpreted to have been deposited in a variety of environments within the main Mount Sharp group stratigraphy, including lacustrine (Gwizd et al., 2022; Stack et al., 2019), fluvial (Edgar

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et al., 2018; Williams et al., 2013) and aeolian (Roberts et al., 2025), and within the Siccar Point group, the aeolian Stimson formation (Banham et al., 2018, 2021, 2022). Aeolian strata record many insights into the conditions under which they formed (Kocurek, 1991; Rubin & Hunter, 1982). For example, the direction in which wind-blown sand dunes migrated are recorded by the cross-lamination dip-azimuths, providing a proxy for the direction of the dominant regional wind at the time of deposition (Bagnold, 1941; Rubin, 1987). Cross-bedding and their accumulated strata was therefore shaped by fluctuations in wind direction and strength as they varied over time. Changes in the orientation of cross-laminations, or a switch between simple and compound cross-bedding can occur over decades or centuries with infrequent changes in wind direction, sand availability and spatial position within the erg (Brookfield, 1977). Higher frequency and shorter duration changes in wind direction can result in predictable changes between facies in interstratified packages (Banham et al., 2022; Lancaster, 1995). Other diagnostic features which can be identified in the stratigraphy include: grain transport mechanisms from the sediment sorting and texture (Banham et al., 2021; Garzanti, 2017; Greeley & Iversen, 1985; McLaren & Bowles, 1985); dune migration processes from bounding surface extent and geometries (Cardenas et al., 2019; Colombero et al., 2024); and sediment availability, which can be inferred from cross-strata morphology or the presence of deflationary supersurfaces (Banham et al., 2021; Mountney, 2006; Porter, 1986). The Naukluft plateau, a large outcrop of the Stimson formation, exhibits many of these characteristics, and so was selected for this study. These characteristics will increase the resolution of understanding of Mars' past wind directions and water table levels.

The objectives of this study are to: (a) describe and characterise the sedimentary textures and facies observed at Naukluft plateau, gaining insight into sediment transport mechanisms; (b) analyse the sedimentary architecture to reconstruct dune morphology and sediment transport direction; (c) describe features associated with diagenetic processes to provide insight to subsurface processes and; (d) compare the Naukluft plateau with other Stimson formation locations to determine the spatial variation in facies and architecture, in order to reconstruct the whole Stimson dune field.

2. Geologic and Stratigraphic Context

At 5.4°S, 137.8°E, Gale crater sits on the Martian crustal dichotomy, separating the heavily cratered highlands from the younger northern plains (Carr & Head, 2010). An impactor formed this 155 km diameter crater, coinciding with the Noachian-Hesperian transition, $\sim 3.7 \pm 0.1$ Ga (Le Deit et al., 2013; Tanaka et al., 2014; Thomson et al., 2011). Gale was partially or completely infilled with sediment over the subsequent 200–500 Ma (Grotzinger, Gupta, et al., 2015; Malin & Edgett, 2000; Thomson et al., 2011), recorded by the 5.5 km high stratified sedimentary mountain, Aeolis Mons (informally and herein “Mount Sharp”), at the crater center (Anderson & Bell, 2010), highlighted in Figure 1 (left insert).

The lower-strata of Mt. Sharp (investigated by MSL), which corresponds to the orbitally identified phyllosilicate bearing strata (Fraeman et al., 2016), includes three lithostratigraphic subdivisions, shown in Figure 2, where vertical elevation is used as a proxy for stratigraphic position due to the predominantly horizontal beds (sensu Banham et al., 2022; Stack et al., 2024). The Bradbury group forms the basal ~ 70 m, and is comprised of interdigitating fluvial, deltaic and lacustrine sedimentary rocks (Edgar et al., 2018; Grotzinger, Gupta, et al., 2015). Overlying this, is the Mount Sharp group, over which Curiosity has traversed >850 m of vertical succession (Banham et al., 2025) - is currently subdivided into three conformable formations: the Murray, the Carolyn Shoemaker and the Mirador formations. The basal Murray formation, comprises more than 300 m (Bennett et al., 2023) of planar-laminated lacustrine mudstones with pockets of cross-stratified sandstones (Fedo et al., 2022; Grotzinger, Gupta, et al., 2015; Gwizd et al., 2020, 2022). The Carolyn Shoemaker formation, is ridge-forming and contains cross-stratified sandstones and interbedded mudstones and sandstones (Cardenas et al., 2022; Fedo et al., 2022). Finally, the Mirador formation records a predominantly aeolian environment, composed of dominant aeolian cross-strata with some fluvial and lacustrine strata (Edgar et al., 2024; Roberts et al., 2025). Higher in the Mount Sharp stratigraphy (not encountered by MSL as of 2025), sulfate-bearing, meter-scale cross-bedded aeolian strata are visible in orbital and Chemcam RMI image data (Milliken et al., 2014; Rapin et al., 2021). These layers comprise the upper-strata of Mount Sharp, and are capped by a lithified package of “duststones”—sometimes described as the Yardang unit (Dromart et al., 2021; Grotzinger & Milliken, 2012).

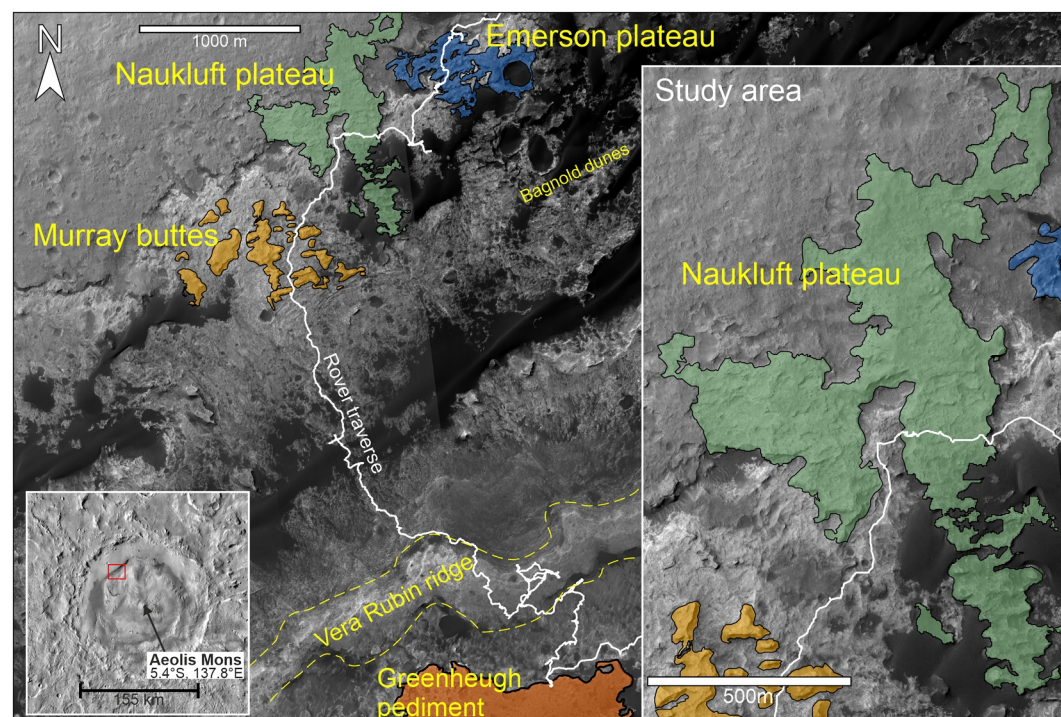


Figure 1. HiRISE orthomosaic showing the traverse of the MSL rover Curiosity south through Gale crater. The colored polygons enclose different regional exposures of the Sinson formation outcrop. The left inset map provides context of the traverse within Gale crater, taken using THEMIS on the Mars Odyssey orbiter (USGS, Mars Regional Mosaic). The right inset map shows the traverse across the Naukluft plateau. The rover traverse path is mapped onto the MSL Gale Merged Orthophoto Mosaic 25 cm/px (Calef & Parker, 2016a, 2016b) in white with the areas of previous Sinson formation exploration outlined and colored (After Banham et al., 2022).

Unconformably overlying the Mount Sharp group is the Siccar Point group, separated by the base Siccar Point group unconformity (Banham et al., 2018; Watkins et al., 2022): an inclined deflational erosive surface mapped across the traverse by Watkins et al. (2022), seen at the outcrop scale in Figure 3a. As of 2025, the Sinson formation is the oldest identified unit of the Siccar Point group encountered by the rover (Banham et al., 2022; Rudolph et al., 2024). The Sinson formation drapes the fluvio-lacustrine sediments which form Mount Sharp (Watkins et al., 2022). The Sinson formation is a cliff-forming, cross-bedded, aeolian sandstone (Banham et al., 2018, 2021, 2022, 2024; Watkins et al., 2022) identified at four key areas along the traverse: the Emerson plateau (Sol 992–1154), Naukluft plateau (Sol 1264–1386), Murray buttes (Sol 1383–1455) and the Greenheugh pediment (Sol 2665–2734), see Figure 1. These locations share the same stratigraphic position, common sedimentary architecture, and mafic geochemical composition (Banham et al., 2021; Bedford et al., 2020; Bedford et al., 2022; Bedford et al., 2022; Yen et al., 2017). The Sinson outcrops above the unconformity span an elevation range of $-4,450$ m and $-4,000$ m (Banham et al., 2022; Bedford et al., 2020; Calef et al., 2016; Yen et al., 2017). The Gediz Vallis ridge strata overlying the Sinson formation is currently tentatively assigned to the Siccar Point group (Davis et al., 2023). Previously, the Sinson formation was orbitally identified and named the “mound skirting unit” (Anderson & Bell, 2010) or the “washboard unit” (Milliken et al., 2014), and extends laterally along the northern flank of Mount Sharp, well beyond the area traversed by MSL (Rudolph et al., 2024).

The width of the Naukluft plateau at the point of traverse spans ~ 250 m, with the thickness of the Sinson formation ranging between ~ 0.5 – 10 m (Bedford et al., 2020; Watkins et al., 2022). The elevation of the Naukluft traverse ranged between approximately $-4,450$ m in the north-east and $-4,420$ m in the south-west (Watkins et al., 2022). However, there were few outcrops of significant vertical exposure along the top of the plateau where the rover traversed (Figure 3b).

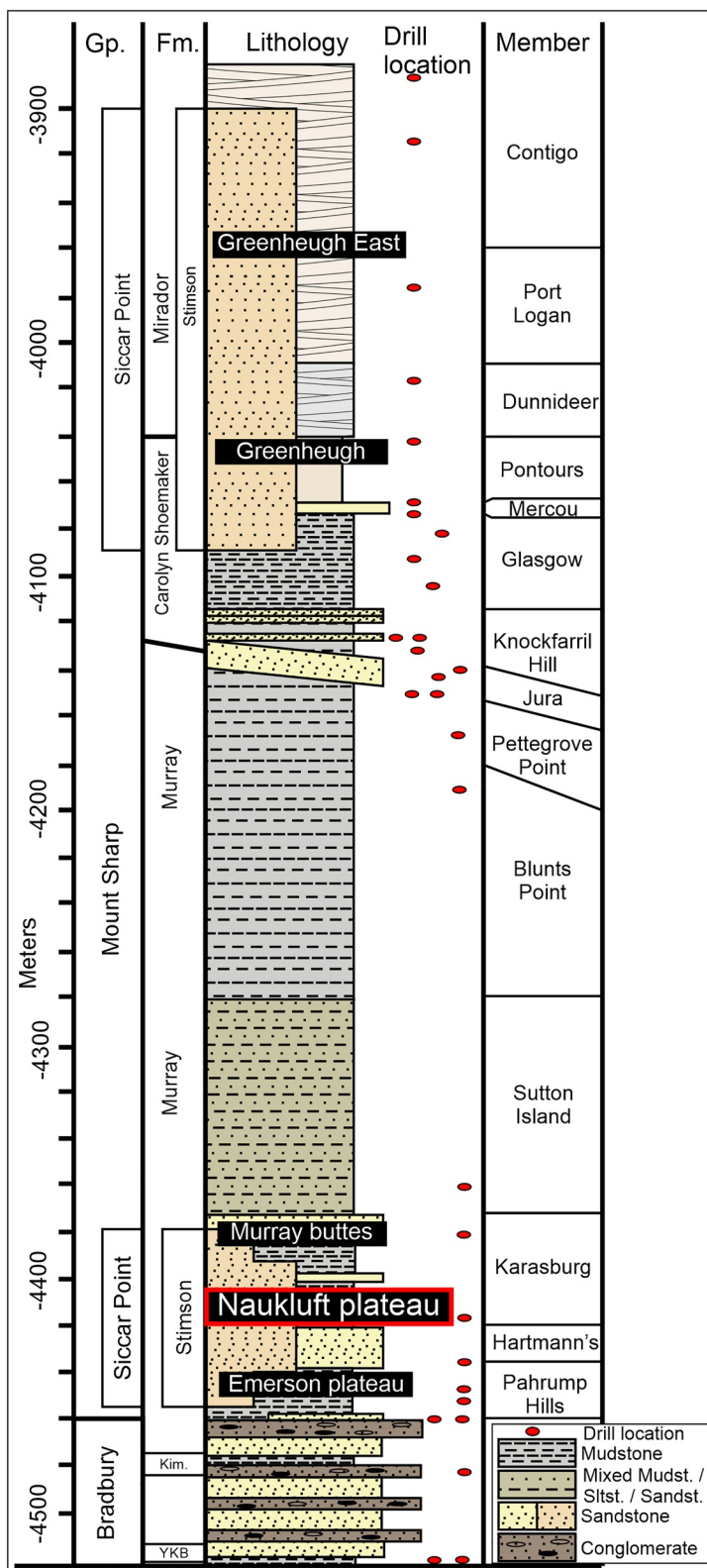


Figure 2. The stratigraphic column discerned by the MSL team showing the context of the Stimson formation. Elevation is indicated on the y-axis and the total stratigraphic thickness of the units is unaccounted for. Stratigraphic column after Banham et al. (2025). Vertical elevation is used by MSL as a proxy for stratigraphic position as the beds are predominantly horizontal.

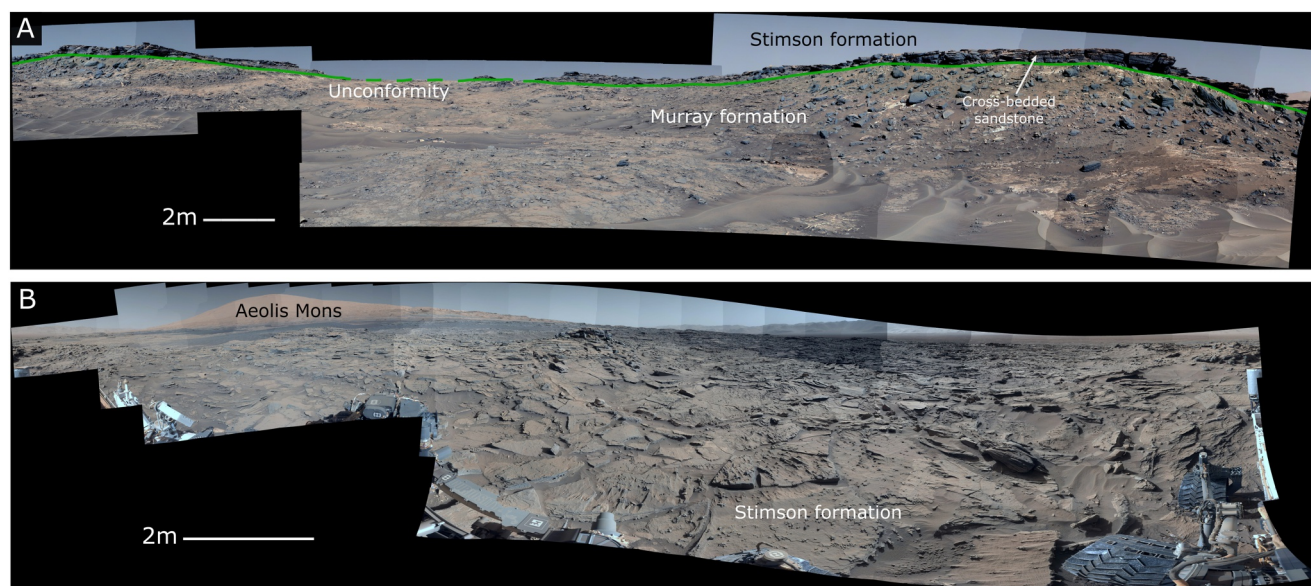


Figure 3. Interpreted mosaics showing the outcrop expressions of the Stimson formation. (a) Mosaic of the eastern margin of the plateau (Sol 1272, MR_mcam005949) highlighting the sub-Stimson, Siccar Point unconformity in green, separating the Murray formation below from the Stimson formation on top. (b) Mosaic taken on the top of the Naukluft plateau (Sol 1282, ML_mcam006031) providing context for the plateau traverse and showing the low-relief nature of the outcrop on top of the plateau. Image credit: NASA/JPL-Caltech/MSSS/JR.

3. Data Collection and Methodology

3.1. Instruments

Photomosaics for sedimentary architecture and facies analysis, were generated from images taken by the Navigation cameras (Navcam) and Mast cameras (Mastcam) on top of Curiosity's Remote Sensing Mast, ~1.9 m above the ground (Bell et al., 2017; Maki et al., 2012; Warner et al., 2016). Mastcam was also used to acquire full RGB color, scientific images of outcrops at 34 and 100 mm focal lengths (Bell et al., 2017; Malin et al., 2017).

The Mars Hand Lens Imager (MAHLI) is at the end of Curiosity's robotic arm and can capture images with a maximum resolution of 14 $\mu\text{m}/\text{px}$ from a working distance of 21 mm (Edgett et al., 2012). The instrument can perform focus merges, merging up to 8 images in a focus stack to generate a composite image with a broader field of focus than the camera generates mechanically. These images were used for grain size analysis within this study.

The digital terrain model and basemap created for MSL, used for location context in this study, comes from 12 HiRISE stereo pairs and data from an array of instruments onboard the Mars Reconnaissance Orbiter (Calef & Parker, 2016a, 2016b; McEwen et al., 2007).

3.2. Data Processing

Images collected by the Mastcam and Navcams underwent radiometric calibration, white balance, and geometric calibration before interpretation (Bell et al., 2017; Maki et al., 2012). Navcam and Mastcam images were mosaiced with geometric adjustments to preserve geometric relations. Using methods described by Alexander et al. (2006), a terrain mesh was generated from Navcam stereopairs to support the measurement of geologic and geomorphic features. Corrected images and mosaics were then interpreted using vector graphics software to highlight outcrop architecture and depositional features. For this paper, stratigraphic and sedimentary features such as unconformities, sedimentary structures and architecture were identified and interpreted using 2D images, before measurements of the morphometrics of sedimentary structures using Digital Outcrop Models (DOMs) were taken, the construction of which is outlined below.

Processed Mastcam frames were used alongside textured 3D outcrop models (DOMs), made from stereo images using Joanneum Research (JR) Planetary Robotics Vision Processing tool (PRoViP; Paar et al., 2022, 2023), to create the meshes used in the VRVis Planetary Robotics 3D viewer (PRo3D; Traxler et al., 2022). MSL Mastcam

PDS data were downloaded from Malin (2013), and processed using the PRoViP 3D vision processing framework (Barnes et al., 2018; Paar & Almer, 1994; Paar et al., 2017, 2022, 2023). To measure depositional features, textured three-dimensional DOMs were generated from Mastcam stereo images using the PRoViP tool (Paar et al., 2012, 2023), and were interpreted using PRo3D (Barnes et al., 2018; Traxler et al., 2018).

3.3. Data Analysis

Initially, two-dimensional interpretations were carried out using vector graphic software. Following 2D interpretation, 3D interpretation using PRo3D was carried out, where important dimensions and geometric features, such as cross-set thickness and cross-lamination dip-azimuth, were measured using the methods outlined in Barnes et al. (2018). For outcrops where stereo data was unavailable, visual estimation methods described by Banham et al. (2018) were used to gauge dip-azimuth. All Navcam and Mastcam mosaic analyses followed standard photogeology methods (De Hon et al., 2001; Moore, 1971; Ray, 1960).

ArcGIS Pro was used to measure grain sizes in MAHLI images (see Banham et al. (2018, 2022) for full methodology). Using a regular grid, grains located at the lower left corner of each square, or the next viable grain after spiraling clockwise outward were selected for measurement. Grains were measured along their longest visible axis. Units were converted to μm by multiplying by the pixel scale, calculated using its linear relations with the working distance, described by Edgett et al. (2012). GRADISTATv8 (Blott & Pye, 2001) was used to analyze the measurements after filtering (Banham et al., 2022), to provide analysis of size and sorting. Sphericity and angularity were determined visually using Powers' index (Powers, 1953).

4. Results

4.1. Sedimentary Facies

Banham et al. (2018) reported four facies within the Stimson formation in the Emerson plateau area. Here at the Naukluft plateau, the cross-bedded facies described are similar to "Facies 2" (Decimeter-scale trough cross-bedding). Other facies identified by Banham et al. (2018), such as meter-scale cross-bedding (Facies 1), and sandstones with Murray formation mudstone clasts (Facies 4), were not identified during this study. Concretions, similar to Facies 3 (Banham et al., 2018), were identified and are common throughout the Naukluft study area. However, these concretions did not occur in sufficient density to overprint and obscure the original depositional structures (cross-bedding), and so do not form a separate facies in this study.

4.2. Decimeter-Scale Compound Cross-Bedding Description

Observation: The compound cross-bedding facies shown in Figure 4 dominate the Naukluft plateau Stimson outcrops. From afar, the Stimson formation is dark gray in color with erosion-resistant ledges and apparent bedding (Figure 4c). Up close, decimeter-thick, cross-bedded sandstones are prominent (Figure 4d), arranged as meter-scale thick cosets between set bounding surfaces. Outcrops at Naukluft are of variable thickness, typically exposing between 2 and 4 cosets forming a vertical succession. Within each coset, a subset (a depositional package bounded by inclined bounding surface, sensu Rubin & Hunter, 1983a, 1983b; second or third order bounding surface, sensu Brookfield, 1977) is composed of uniformly spaced, parallel cross-laminations of millimeter-scale thickness, which vary minimally along their length. The cross-laminations transition along their length from straight to asymptotic at the base (Figure 4d). However, in some of the thinnest preserved cross-sets, the cross-laminations can appear more like horizontal laminations; this is because only the basal section of the asymptotic cross-laminations is preserved. In addition, there was an irregular pattern of protruding and indented cross-laminations (Figure 4d). Concretions can be found in cross-sets throughout the Stimson formation; however, they are typically concentrated in the lower parts of the formation, especially in the basal sections. Measured diameters range between 15 and 100 mm, and they are typically spherical to slightly oblate. Remnant cross-laminations can be discerned in the cross-section of some concretions.

Interpretation: The decimeter-scale cross-bedding represents the preserved lower portion of a dune lee slope, however, due to their scale, the bedform they result from could be: (a) a superimposed dune migrating over a dune or primary bedform lee slope (Rubin & Hunter, 1987); (b) cross sets deposited by a large-scale aeolian dune which was deeply scoured by a successive dune or; (c) the preserved cross-sets formed by a large ripple, similar to those identified in modern Martian dune fields, which are a result of sediment transport processes in a thin atmosphere

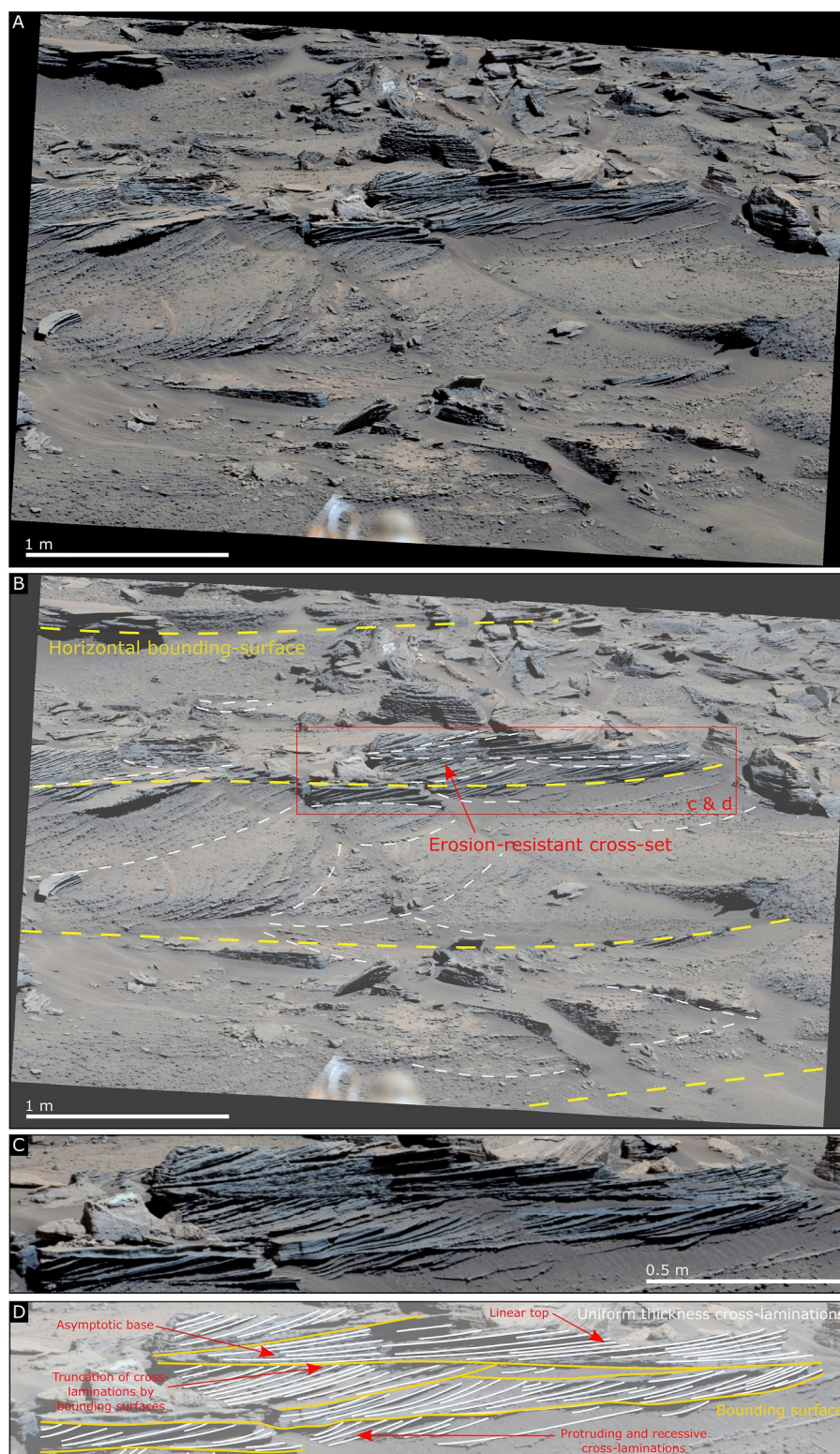


Figure 4. Representative examples of cross-bedding observed on the east side of the Naukluft plateau, acquired on Sol 1277 (MR_mcsm005998). (a) Uninterpreted mosaic. (b) Annotated mosaic of the decimeter-scale cross-bedding depicting the representative depositional structures for the Stimson formation at the Naukluft plateau; the compound cross-bedding is highlighted on a larger scale, with set bounding surfaces in yellow. (c) Uninterpreted close-up of the asymptotic cross-laminations, highlighting their uniformity. (d) Annotation of the outcrop architecture, defining the subset bounding surfaces classifying them as compound cross-bedding. Image credit: NASA/JPL-Caltech/MSSS/JR.

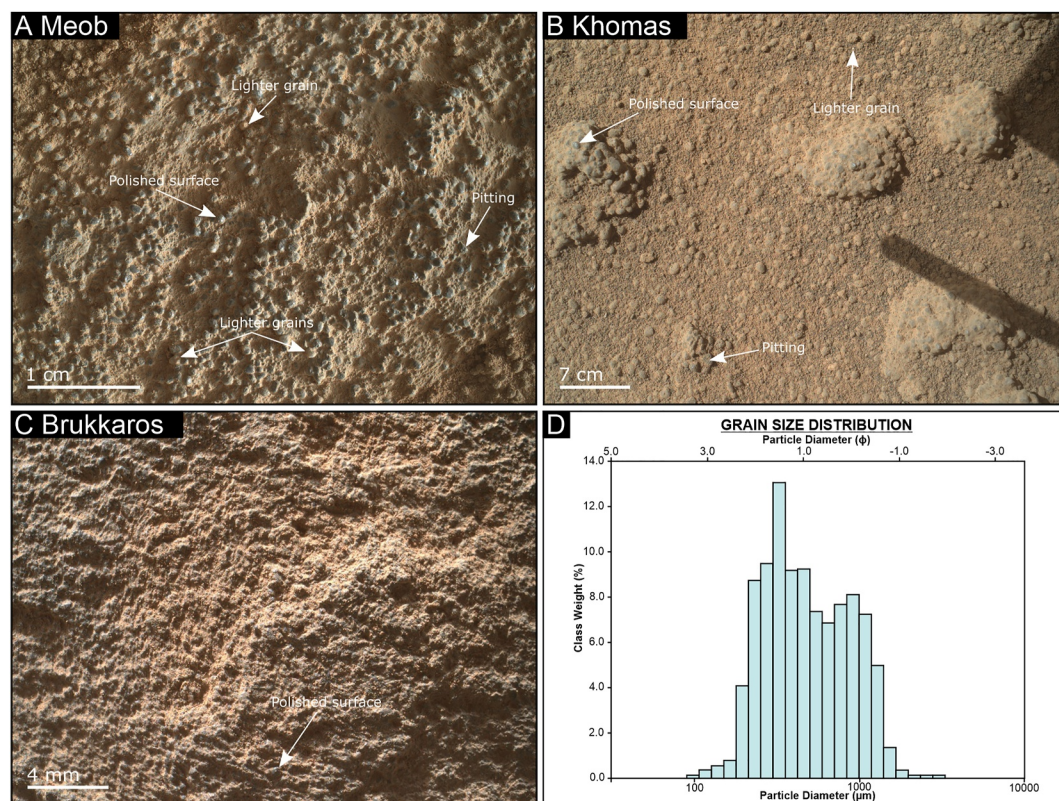


Figure 5. The images used to complete grain size analysis of Stimson sandstones and the resulting histogram of particle diameters. (a) Grains imaged on Sol 1348 at Meob using MAHLI. (b) Close up image of the Stimson formation sandstone taken on Sol 1279, at Khomas. Note the ~90 mm concretions, which are composed of sand grains. (c) MAHLI image consisting of the Stimson formation sandstone imaged on Sol 1295, at Brukkaros. (d) Histogram of the cumulative 844 grain measurements taken from the three images (a–c). Image credit: NASA/JPL-Caltech/MSSS/JR.

with a high kinematic viscosity (Lapotre et al., 2021; Sullivan et al., 2020). The cross-sets observed in this study area, are similar to the small scale of the cross-sets observed at Marias Pass by Banham et al. (2018), and the subsets observed at the Murray buttes by Banham et al. (2021). In both cases, these smaller cross-sets are interpreted to be subsets formed by the migration of superimposed bedforms (*sensu* Brookfield, 1977); this is the preferred interpretation for the origin of these cross-sets at the Naukluft plateau. The cross-laminations that compose these types of cross-sets are produced by wind ripple migration due to their uniformity, distinctive of pinstripe laminations produced when wind-ripples migrate across lee slopes, re-working previously deposited sediment (Eastwood et al., 2012; Fryberger & Schenk, 1988; Hunter, 1977). The concretions are interpreted to have formed post-deposition during the diagenesis process. Preferential growth of cement through the pore spaces will occur from a chemically saturated pore fluid (Siebach et al., 2017). The concretion will originate from a nucleation point (potentially a piece of detrital Murray formation, although not visually confirmed; Banham et al., 2018).

4.3. Sedimentary Texture

Description: Grains were measured using MAHLI images of the Stimson formation at the Naukluft plateau taken at the Khomas (Sol 1279), Brukkaros (Sol 1295) and Meob (Sol 1348) targets (Figure 5). These MAHLI targets were selected as grains were clearly visible and well-defined and the images provide a representative sample of locations across the Naukluft plateau. The grains display moderate sphericity, are moderately well-rounded and have an arithmetic mean grain size of 482 μm (Figure 5d). Combined, the 844 measurements exhibit a broadly bimodal grain-size distribution with end members measuring 89 and 2,606 μm (Modes 327 μm ; 925 μm ; $D_{75} - D_{25} = 490 \mu\text{m}$) and are therefore moderately sorted (Figure 5d). Overall, the samples are medium-grained sandstones composed of gray grains with smooth surfaces.

The MAHLI image taken at the Khomas target consisted predominantly of (~40%) very fine to medium-sized sand grains (Figure 5b). The remaining composition is of coarse to very-coarse sand grains (~53%), producing a bimodal distribution and poor sorting. Larger grains (>700 μm) are relatively consistent in their gray coloring whilst some smaller grains range from beige to white (Figure 5b), with >40% nearing dark gray or black. Sand grains not coated in dust show a very polished surface, nearing vitreous, and others indicate slight pitting, as shown in Figure 5b. Uniquely, Brukkaros is a unimodal, well sorted, medium sand, with only 2.7% of grains coarser than medium sand. In the Brukkaros sample, sand grains exhibit less color variation than at Khomas, and grains do not generally weather as proud as other targets (Figure 5c). All smaller grains range in the same beige to white color spectrum with gray larger grains, and exhibit the same smooth surface; however, pitting is less apparent. Brukkaros' grains appear well-sorted, due to the narrower distribution in grain sizes, unlike Khomas (Figure 5b) where some larger grains look to be weathering from the finer grained matrix. Sand grains at Meob are protruding further out of the sandstone than in other locations and the larger grains appear less tightly packed (Figure 5a). In Meob, the distribution of grain sizes is bimodal (like in Khomas); however, >75% of grains are medium to very coarse. Pitting is quite prominent in some grains and many of the large grains exhibit their near-vitreous, smooth surfaces (Figure 5a). The very-fine sand grains are beige in color mixed evenly with some dark gray grains. However, unlike Khomas and Brukkaros, >5% of larger grains in Meob are lighter gray or beige.

Interpretation: A bimodal grain-size distribution and significant rounding are distinctive features of aeolian sediments (Folk, 1980; Sharp, 1963). Transport in other environments, such as sub-aquous environments, is not as effective at rounding grains (Twenhofel, 1945) and saltation can increase the size of particles transported by engaging surface creep (Banham et al., 2018; Greeley & Iversen, 1987). Lofting and high velocity impacting easily round grains (Garzanti, 2017), which may be particularly relevant considering that a significant part of Mars' aeolian transport is via reptation (Marshall et al., 1999). On Earth, aeolian transported sediments found in dunes fall across a broad grainsize range (0.1–2 mm), effectively all sand-size particles (Ahlbrandt, 1979; Wentworth, 1922, 1933), and the Naukluft grains fall within that range, although these grains are coarser than those Bagnold (1941) described on Earth (150–300 μm). Preston (2023; Preston et al., 2024) deduced that the source for the Stimson sandstone was more proximal to the sediment source area; therefore, the grains are coarser due to transportation via surface creep. There are two modal peaks (Figure 5d): one at 327 μm which represents the smaller fraction of grains transported by saltation; and a second at 925 μm which represents sediment transported by surface creep (sensu Banham et al., 2018). However, the sediments measured are considered moderately sorted, which lends itself to a fluvial environment (Pye & Tsoar, 2008), but can be explained by (a) the type of dune (individual dunes are more likely to be well sorted than dune ridges (Lancaster, 1982)) and (b) how far down-wind the grain has been transported, as the further from the source, the better sorted the grains are (Folk, 1978; Pye & Tsoar, 2008). The limited variety in grain color is attributed to differences in mineralogy. Darker mafic minerals—specifically olivine—are easier to transport owing to their round shape and travel further than felsic minerals (Bedford et al., 2020), providing one explanation for the rarity of light-colored (felsic) large grains.

4.4. Variations in Facies Across the Plateau

The plateau has been arbitrarily split into an eastern (Sol 1264–1284), central (Sol 1285–1355) and western section (Sol 1356–1381) based on geographic location (Figure 6) to evaluate spatial variation in sedimentology and stratigraphy of the formation across the plateau. Establishing the scale at which facies change laterally within the Stimson formation at the Naukluft plateau allows for deeper insight into variations of the depositional processes across the plateau, reflecting sub-environments within the ancient dune field.

4.4.1. Eastern Side of the Plateau

The eastern side of the plateau is illustrated in Figures 3, 7 and 9, and is exemplified by the Sol 1275 and 1267 outcrops. The Sol 1275 outcrop is 2.5 m tall by 11.5 m wide and is composed of two units (Figure 7b). The Murray formation is seen at the base, identified by its recessive weathering pattern, brown color and absence of cross-bedding (Figures 7a and 9a). Above, the Stimson formation is identifiable as an erosion-resistant, cliff-forming unit, blue-gray in color with abundant cross-bedding (Figures 7a and 9c). These units are separated by the base Stimson unconformity, as defined by Banham et al. (2018) and mapped by Watkins et al. (2022), which undulates on a decimeter scale, but is often obscured by talus shed from the Stimson formation.

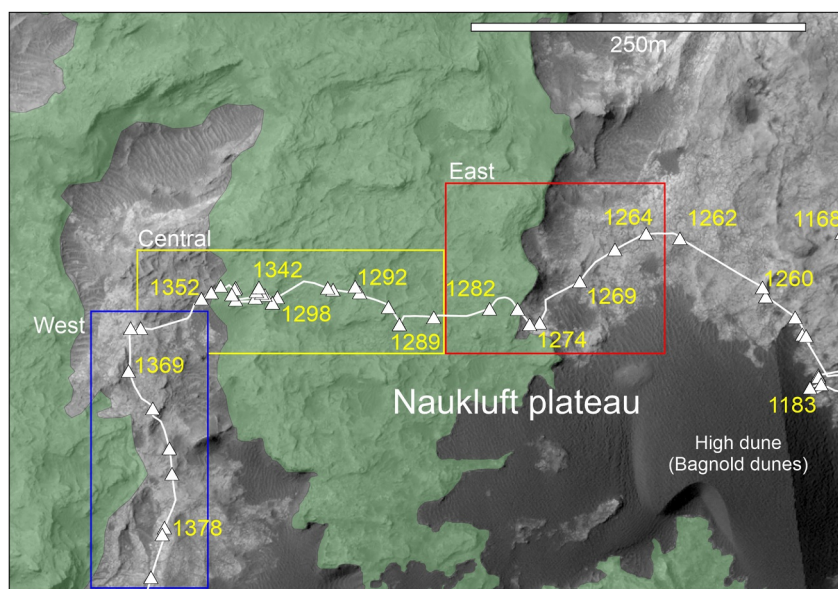


Figure 6. The Naukluft plateau traverse is split into three areas for comparison: eastern (Sol 1264–1284; red box), central (Sol 1285–1355; yellow box) and western (Sol 1356–1381; blue box). This is mapped onto the MSL Gale Merged Orthophoto Mosaic (Calef & Parker, 2016a, 2016b). Image credit: NASA/JPL-Caltech/U. Arizona.

Figures 7b, 9b, and 9c depict interpretations of the sedimentary architecture on the east side of the plateau. The characteristic asymptotic curve of the cross-laminations (traced in white; Figure 10), dip steeply at the top of the cross-set and decrease in inclination toward the base of the set (Figure 10a). Cross-laminations are uniformly spaced, maintain thickness along their length and conform to a loosely alternating sequence of depression and protrusion, highlighted in Figure 10d. The Sol 1275 outcrop was imaged in stereo, allowing a DOM to be generated for measurement of sedimentary architecture. Cross-laminations at the Sol 1275 outcrop have dip-azimuths with a preferred orientation to the north (Figure 8b), and to the north-northeast at the Sol 1267 location, indicating the sediment transport direction at the time of deposition. Packages of cross-laminations are truncated by the inclined erosional surfaces, and each coset is bound by sub-horizontal upper and lower erosional surfaces (Figures 7b and 10d). Whether the outcrop exhibits predominantly trough or planar cross-bedding is difficult to discern as scree obscures most subset erosional surfaces used to determine the different geometries (Figures 7 and 9). Figure 8a shows the variability of cross-set thicknesses at the Sol 1275 outcrop depicted in Figure 7. These measurements were made using the DOM derived from stereo images of the outcrop. Thickness averages at 10.9 cm ($n = 62$), with a range of 3.7–66.3 cm. The distribution of cross-set size does not adhere to any vertical trends or patterns: there is no systematic upward increase or decrease in cross-set thickness.

The Sol 1275 outcrop has areas containing concretions amongst the cross-bedding, as highlighted in Figure 10b. These centimetre-scale spheroidal concretions are embedded within the cross-bedding, eroding as prominent weathering-resistant features. In many cases, concretions have amalgamated, creating a lobulated appearance. The concretions increase in quantity toward the lower 1 m of the outcrop as well as covering a few randomly distributed cross-sets higher up (Figure 7a). However, there are few or no appearances of concretions in the uppermost 0.5 m of the outcrop. This changes slightly for the largest outcrop on Sol 1267 (Figure 9c) where ~40% of the subsets have concretions, but a large accumulation is central to the outcrop, whereas others appear randomly distributed elsewhere. The Sol 1267 outcrop (Figure 9c) also displays several sub-linear, fracture-associated diffuse white halos which extend up the outcrop, reaching widths of >0.5 m (Figure 10c). This alteration extends across cross-sets and follows natural pathways between them, decreasing in size toward the top and not bound to the outcrop base unlike the concretions. Sol 1275 outcrop does not have any such features, but the Murray formation contains white veins which truncate at the unconformity (Figure 7b). This is similar to the Sol 1267 and 1272 locations (Figures 3a and 9), where the alteration encroaches into the Stimson formation, but the largest patches remain within the Murray formation, skirting the unconformity.

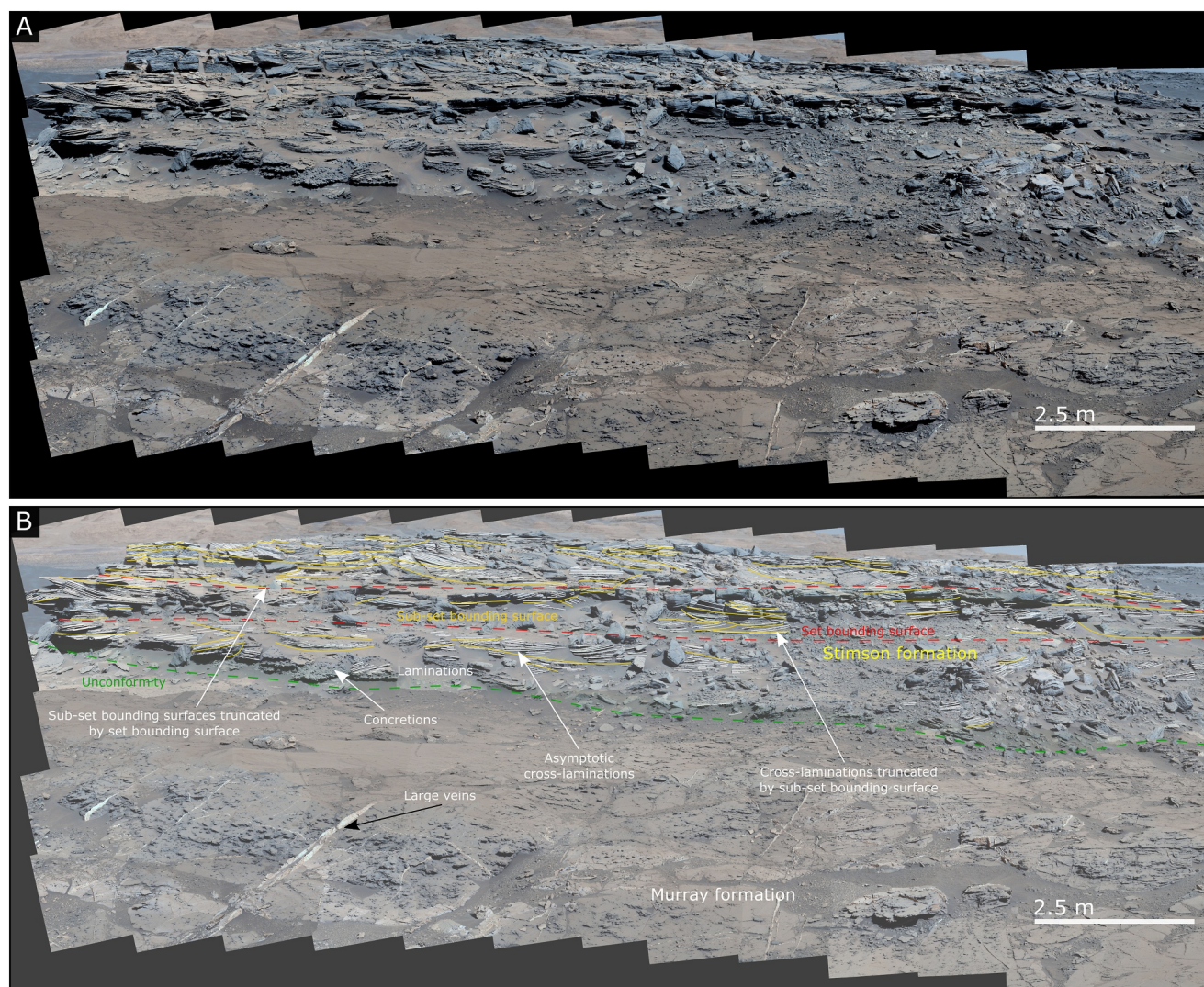


Figure 7. (a) Unannotated mosaic captured on Sol 1275 (mcam005976). (b) Interpreted sedimentary architecture of the outcrop imaged on Sol 1275 showing the three cosets and Siccar Point unconformity in green. Red dashed lines separate cosets, representing set bounding surfaces, and sub-set bounding surfaces are annotated in yellow. Image credit: NASA/JPL-Caltech/MSSS/JR.

4.4.2. The Central Plateau

The ~1.75 m high vertical section of Stimson formation imaged on Sol 1296 is formed of two cosets, each containing decimeter-scale cosets of cross-bedding (Figure 11b). Here, the rover was traversing the top of the plateau, so neither the Murray formation nor the unconformity was observed. The sedimentary structures and architecture mirror that of the eastern plateau; uniform cross-laminations curve asymptotically, terminating at the subset erosional surfaces (annotated in yellow, Figure 11b), maintaining even thickness, regarding their spacing and laterally along their length. The cross-tilination dip-azimuths are also trending to the north-northeast (Figure 11d), likewise for the Sol 1285 and 1348 outcrops in Figures 11c and 12a. The Sol 1285 and 1296 set bounding surfaces persist for the length of the outcrops and the subset bounding surfaces terminate against them (Figure 12b). The uppermost and lowermost set bounding surfaces cannot be seen due to modern sediment cover and mosaic extent in both Figures 11b and 12b. Sol 1296 cross-sets average 10 cm thick ($n = 51$); the thickest cross-set measured 43 cm, the smallest only 2 cm. The cross-laminations and subset bounding surfaces at the Sol 1296 outcrop are less bowed than on Sol 1275 (Figure 7b).

Few cross-sets in this outcrop contain concretions and where present, they are in the lowest exposed cosets. Within each subset, concretions are less densely packed and scarcer than within the Sol 1275 outcrop (Figure 7).

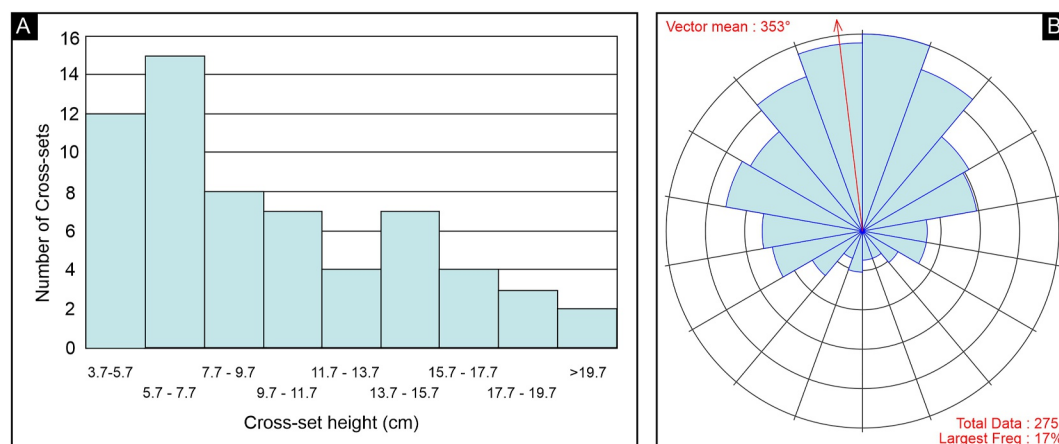


Figure 8. Quantitative data measured from Sol 1275 Digital Outcrop Model (DOM). (a) Histogram of 62 cross-set thickness measurements from the Sol 1275 outcrop. Cross-set thicknesses are subdivided by Jenks natural breaks. (b) A rose plot of the dip-azimuth measurements taken on the outcrop imaged on Sol 1275. Vector mean: 353°, Vector magnitude = 0.62; $n = 275$.

The same applies to the outcrop imaged on Sol 1285, where fewer concretions are visible in the lower left of the mosaic (Figure 12a). Figure 11c, Sol 1348, shows the same decrease in concretions away from the outcrop base; however, some concretions appear in cross-sets higher in the stratigraphy (lower left of mosaic). Fewer concretions in the central plateau appear to have coalesced as they remain sub-spheroidal, again indicating that the exposed stratigraphy is not immediately adjacent to the basal unconformity. The Sol 1296 outcrop display areas of alteration similar to those previously noted at the outcrops imaged on Sol 1267 (Figure 9). However, there is only one white vein central to the mosaic, highlighted in Figure 11a, with alteration of the rock to the left of the vein, from gray to beige. The outcrop also presents multiple broken blocks containing similar features; the host rock appears to be a Stimson formation; however, as it is not in situ, their origin is less certain.

4.4.3. Western Side of the Plateau

Much of the outcrop imaged on Sol 1368 (Figures 13a and 13b) is covered with recent superficial sands and similar to the central plateau, the unconformity and Murray formation are not observed in any mosaics. Outcrops

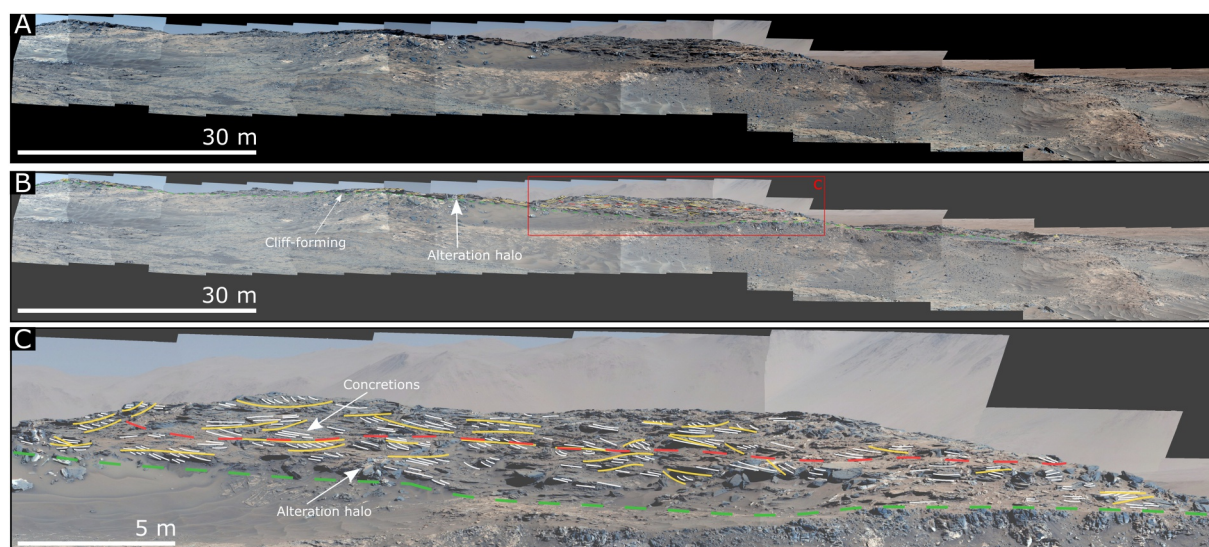


Figure 9. Examples of the Stimson formation's cliff-forming nature and the compound cross-bedding observed along its extent, above the Siccar Point unconformity. (a) Uninterpreted panoramic mosaic taken on Sol 1267 (mcam005946). (b) Annotated panorama highlighting the unconformity extent, mapped in green. (c) Interpreted close up of the largest outcrop imaged on Sol 1267 showing the compound cross-bedding separated into two cosets by the red dashed lines. Image credit: NASA/JPL-Caltech/MSSS/JR.

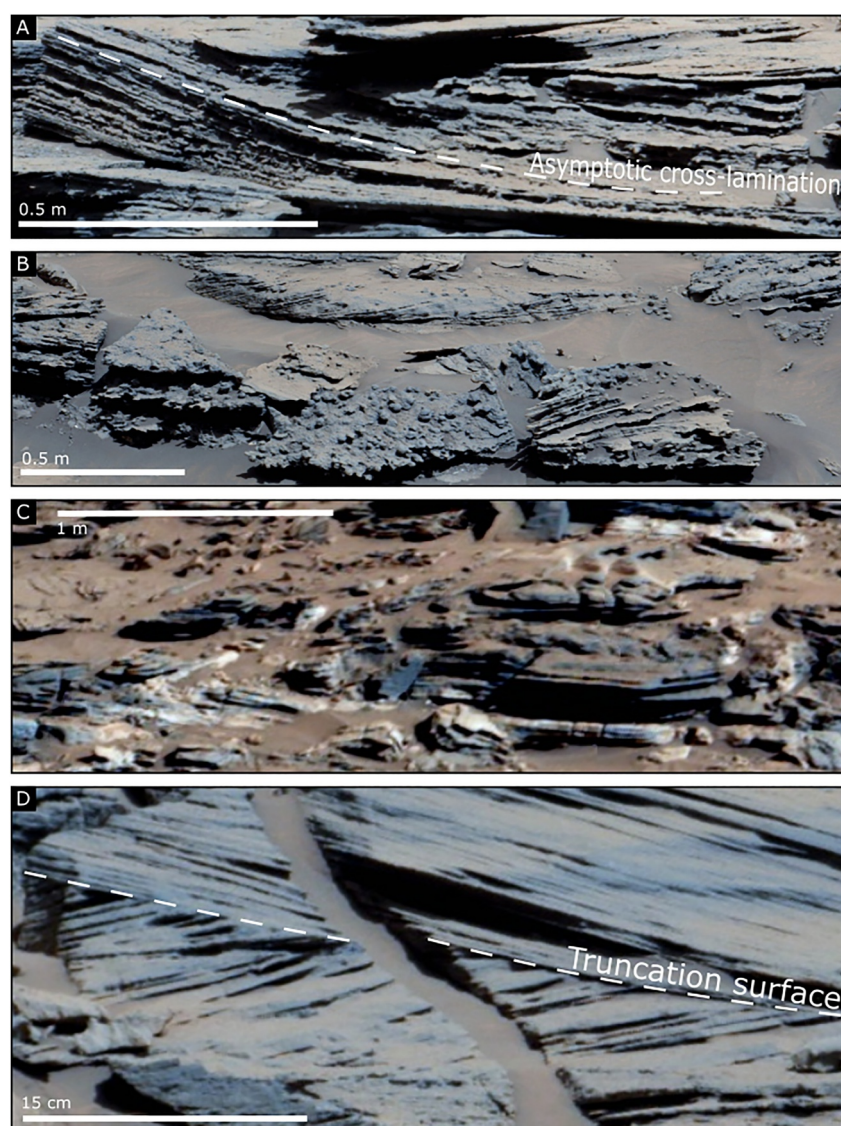


Figure 10. Magnified examples of notable features of the Stimson formation in the eastern section of the Naukluft plateau, imaged on Sol 1275 (mcam005976). (a) Sub-frame from the Sol 1275 mosaic, highlighting the uniformity of the cross-laminations in the Stimson formation and their transition from linear to curved, creating the characteristic asymptotic shape. (b) The concretions seen at the base of the Sol 1275 outcrop. (c) One of the alteration halos displayed on the Sol 1267 outcrop. The alteration forms a lenticular shape, surrounding one of the cross-sets. (d) Exhibiting the truncation of cross-laminations against bounding surfaces on Sol 1275 as well as the protrusion and indentation of alternating cross-laminations. Image credit: NASA/JPL-Caltech/MSSS/JR.

contain cross-laminations that are characteristic of the Stimson formation in other locations (Figure 13b): laminations have uniform thickness which is consistent along their length, are evenly spaced with alternating prominent-recessive surfaces and are parallel to adjacent laminations within the same set. Most cross-laminations are decimeter-scale in length, with few reaching lengths greater than 1 m. Cross-laminations appear largely linear and their associated subset bounding-surfaces are inclined in a similar direction, at slightly lower angles (Figure 13b). The horizontal set bounding surfaces are laterally persistent, spanning the outcrop length with minor undulation, separating the outcrop into three ~ 2.5 m cosets. Dip-azimuths of cross-laminations are oriented to the north-east for the Sol 1368 outcrop and to the north for the Sol 1381 outcrop. Most features between the outcrops on Sol 1368 and Sol 1381 are similar; however, the set bounding surfaces cannot be traced along the Sol 1381 outcrop, due to sand cover and thin outcrop exposure (Figure 13d).

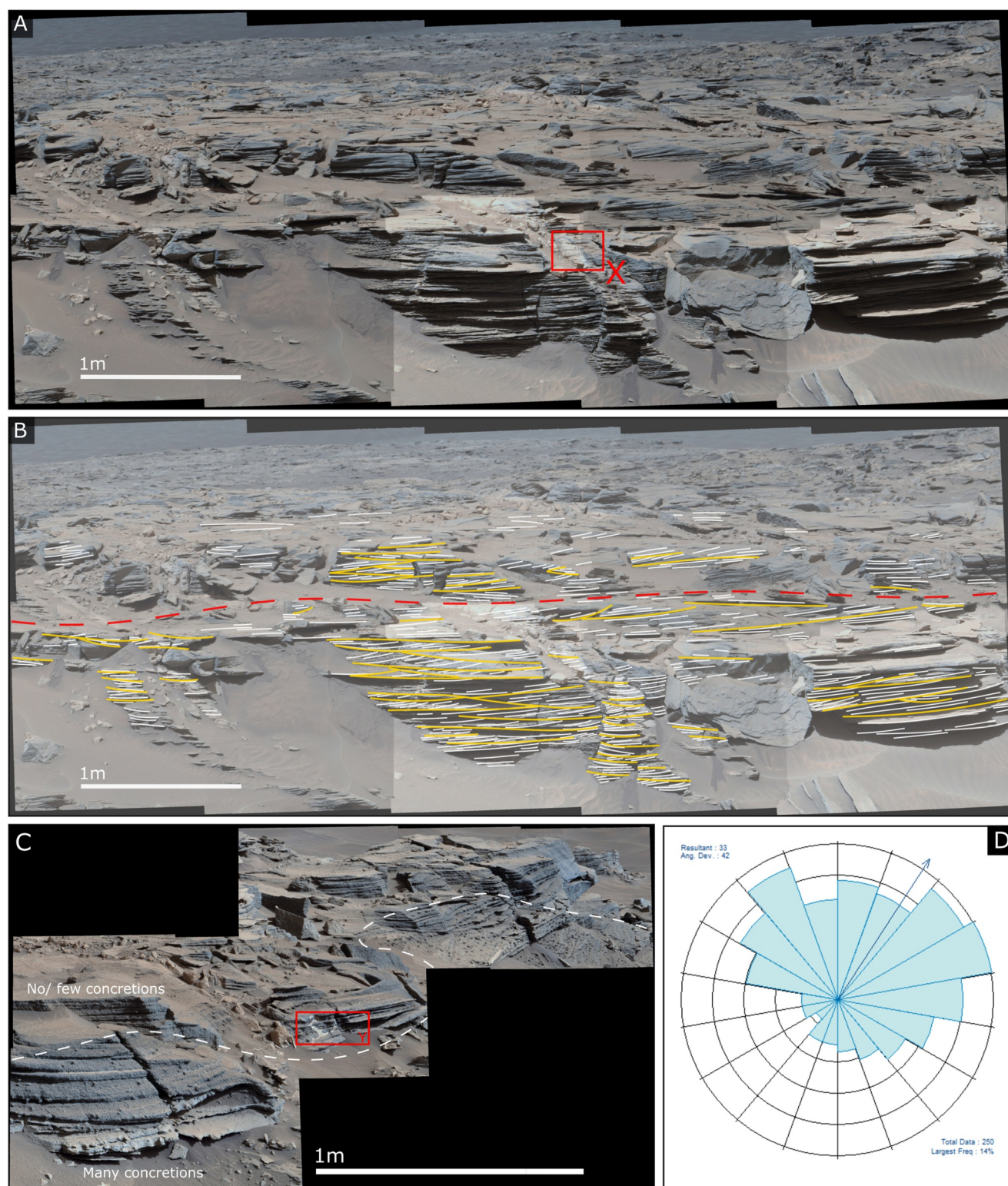


Figure 11. Representative examples of the cross-bedding, the pattern of concretion distribution and the cross-lamination dip-azimuth in the central area of the plateau. (a) An unannotated mosaic from Sol 1296 (MR_mcam006155). X shows a vein with alteration on its left. (b) Annotated outcrop imaged on Sol 1296 depicting two cosets, split by the red dashed line defining it as the set bounding surface. (c) A mosaic taken on Sol 1348 (mcam006463) highlighting compound cross-bedding as well as a decrease in concretions from the base to the top, shown by the annotations in white. Y is highlighting a prominent white vein in the outcrop. (d) Rose plot of the dip-azimuth for the outcrop seen in a and b on Sol 1296. Image credit: NASA/JPL-Caltech/MSSS/JR.

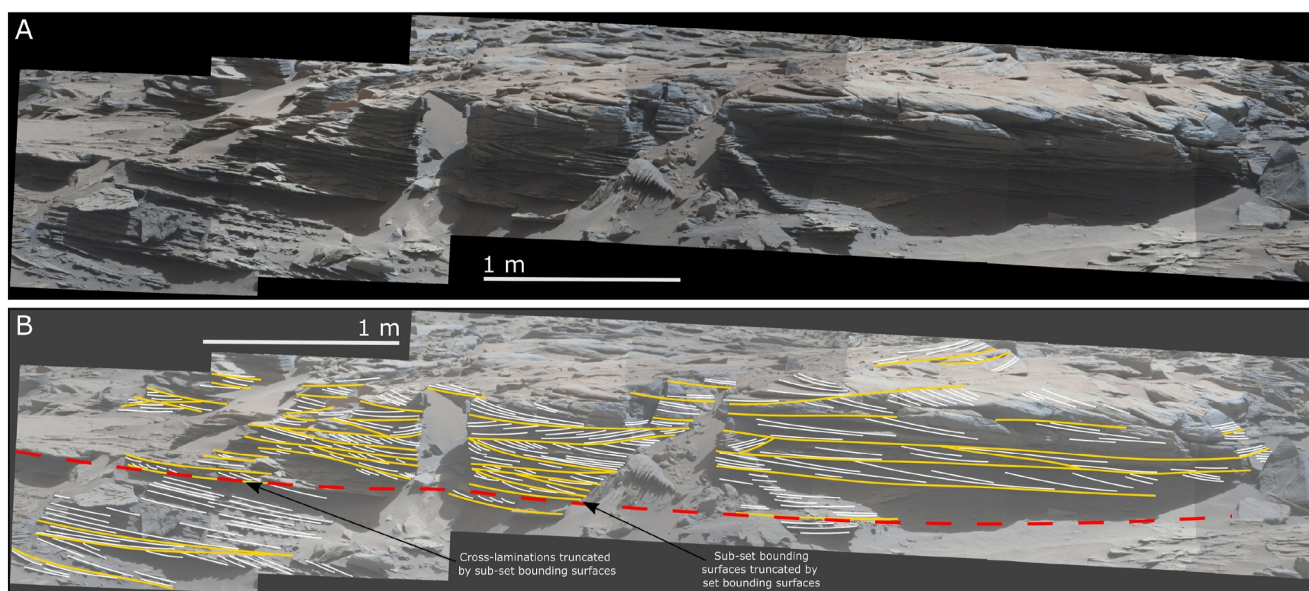


Figure 12. (a) An uninterpreted mosaic up of Sol 1285 (mcam06072). (b) Sol 1285 annotated to show the decimeter-scale compound cross-bedding split into two cosets. Image credit: NASA/JPL-Caltech/MSSS/JR.

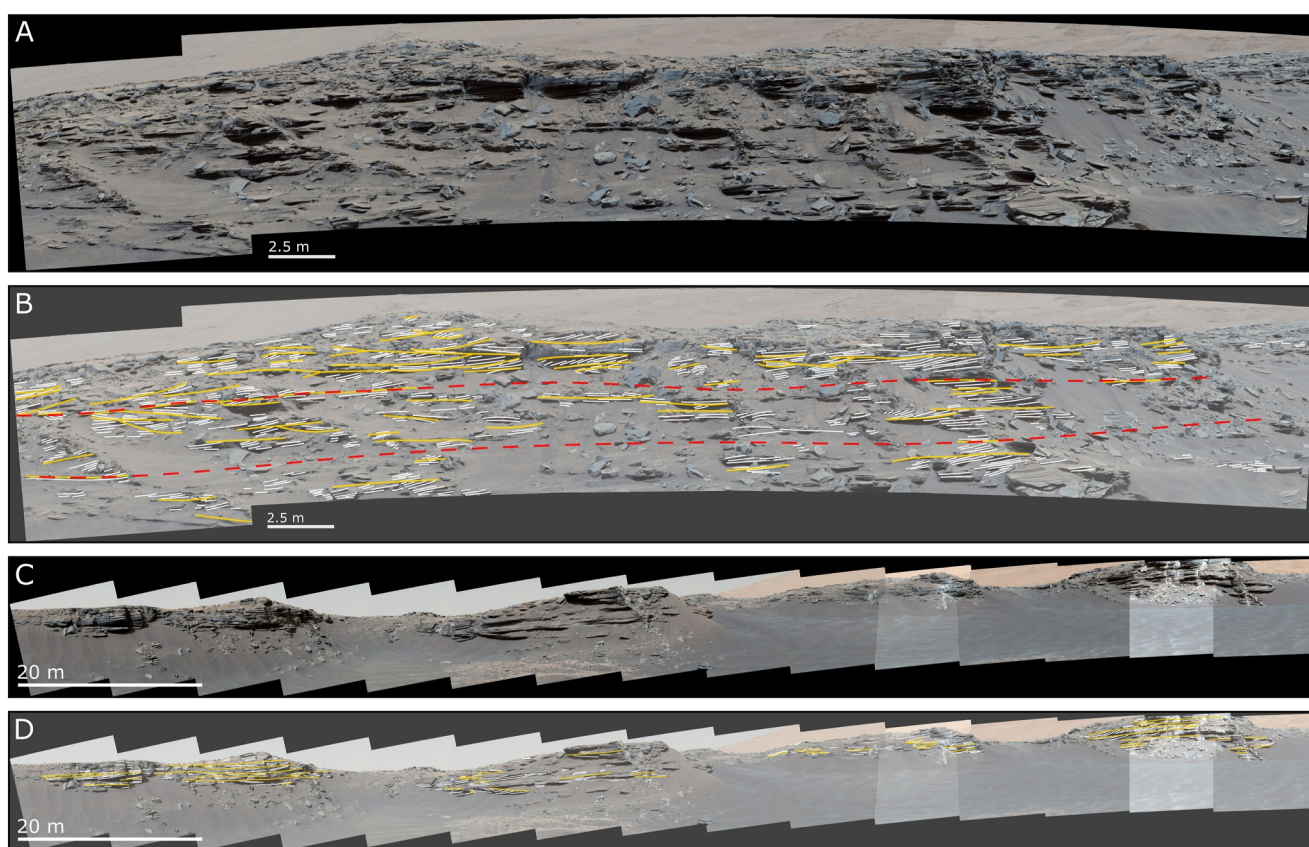


Figure 13. Examples of the cross-bedding observed at the western section of the Nauyluft plateau. (a) Mosaic of the outcrop imaged on Sol 1368 (MR_mcam006695). (b) Annotated mosaic from Sol 1368, which is composed of three cosets similar to Sol 1275. (c) Unannotated mosaic from Sol 1381 (MR_mcam006770). (d) Interpreted outcrop from Sol 1381, which has no identifiable set bounding surfaces and the unconformity cannot be seen. Image credit: NASA/JPL-Caltech/MSSS/JR.

Table 1

A Comparison of the Measured Cross-Set Thickness at Each of the Large Areas of Stimson Formation Outcrop, Inclusive of This Study

Stimson formation outcrop	Cross-set thickness (min-max range in m)
Emerson plateau	0.05–1.0
Murray buttes	0.3–1.4
Greenheugh pediment	0.15–0.8
Naukluft plateau	0.02–0.65

Note. Measurements taken for the Emerson plateau, Murry buttes and Greenheugh pediment were by Banham et al. (2018, 2021, 2022) respectively.

The Sol 1368 outcrop continues the trend of concretions decreasing in quantity toward the outcrop top. Several concretions appear to have agglomerated whilst others maintain a sub-spherical shape. Fine details are difficult to resolve for the Sol 1381 outcrop due to outcrop distance; there are coarse textures which may be concretions, but it is mostly unresolvable (Figure 13c). The center of the Sol 1368 outcrop contains some diffuse, decimeter-scale, white alterations, but these halos predominantly coat scree or fallen blocks (Figure 13a). Sol 1381 outcrops, however, show significant alteration halos (Figure 13c); they can be traced vertically up the extent of the right-most outcrop, following fractures and descend the scree at the outcrop base. From left to right of Sol 1381 outcrops, Figure 13c, there is a decrease in quantity and size of the white alterations until there are none on the leftmost outcrop.

4.4.3.1. Interpretation of Plateau Outcrops

The Siccar Point unconformity separates the Stimson formation from the Murray formation (Figure 3a). At the Naukluft plateau, the unconformity is observed at the east of the plateau but extrapolated along the base of the central and western sides. When viewed perpendicular to regional dip, the Stimson formation forms a near horizontal stratal unit along strike and is therefore in its depositional orientation (Stein et al., 2020); however, the bedding of the Murray formation is cross-cut by the unconformity. Due to the lack of tectonics and limited subsequent fluvial erosion, aeolian-driven exhumation is the likely explanation (Watkins et al., 2022), defining this unconformity as a deflation surface (Banham et al., 2022; Watkins et al., 2022).

Cross-bedding at the Naukluft plateau is architecturally similar to that observed at the Emerson plateau, Murray buttes and the Gleann Beag section of the Greenheugh pediment (Banham et al., 2018, 2021, 2022) in all apart from cross-set scale (Table 1). Some Naukluft plateau cross-sets fall within the typical range of Stimson cross-set thickness (0.3–1.0 m), but most are measured to be below 30 cm thickness. If the same Stimson formation interpretation of aeolian bedform migration is to be applied, these small cross-sets would correspond to super-imposed bedforms found across the draa lee slope (Figure 14b). Brookfield (1977) and Kocurek (1981) classify bounding surfaces associated with bedforms hierarchically. Set bounding surfaces, annotated in red for all figures, can be traced for most of the length of the outcrop straddling each coset; however, subset erosional surfaces, traced in yellow, separate cross-sets and are of a similar scale.

The varying dip-azimuth between cross-sets in a coset observed at the Naukluft plateau negates the hypothesis that subset bounding surfaces are reactivation surfaces (Rubin & Hunter, 1982, 1987; Hunter and Rubin); >80% of the measurements in Figure 11d are from one coset, and the variety in dip-azimuth spans over 180°. This could indicate that the cross-bedding here is trough cross-bedding and that dune crests were sinuous, even on super-imposed bedforms.

Cross-sets may be thinner due to a down-slope migration direction, as shown in Figure 15c. Watkins et al. (2022) showed that the regional slope of the unconformity decreases from the south-west to the north-east of the plateau. This orientation is the same as the sediment transport direction deduced in this study, and by Bedford et al. (2020), who compared the geochemistry and mineralogy of the Stimson formation to that of possible sediment sources, considering aeolian mineral sorting processes during transport. Further, if the rate of accumulation is significantly lower than the rate of down-wind migration of sediment, then it is likely the cross-sets will thin as the angle of climb decreases in response (Mountney, 2012; Figure 15b). Topography of the unconformity is spatially variable and sediment supply was temporally variable, which works in tangent with the autocyclic factors such as the migrating dune's height and scour depth (both which are variable over time; Figure 15a; Kocurek & Day, 2018) and results in variations of cross-set thickness along the trace of the cross-set that records a dunes migration (Colombera et al., 2024; Reesink et al., 2015). Colombera et al. (2024) stated that dune preservation is “variability-dominated,” therefore defining what a standard cross-set morphology (e.g. thickness and cross-lamination dip profile) should be is untenable due to the inherent lack of consistency between successive dunes which form each cross-set.

With cross-sets measuring predominantly <1 m, formation in a sub-aqueous setting must be considered as, on Earth, cross-sets this small often indicate a fluvial facies (Banham & Wakefield, 2015; Cross et al., 2023; Priddy

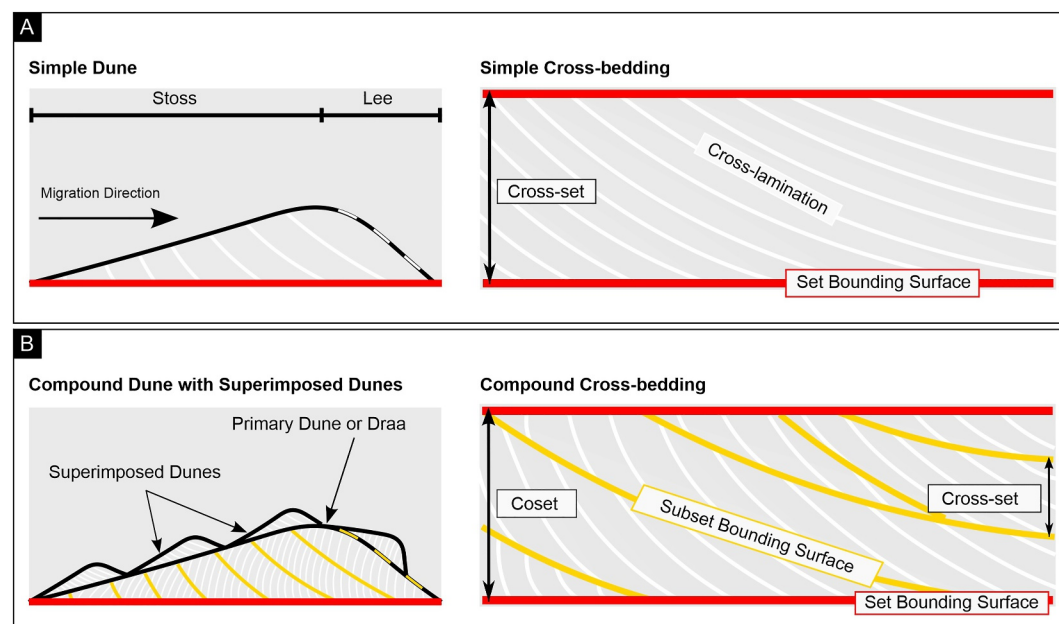


Figure 14. (a) Idealized representation of the formation of simple cross-bedding from a single dune. The characteristic asymptotic cross-laminations truncate the lower bounding surface forming a cross-set. (b) Idealized schematic of the formation of compound cross-bedding and the relation to the hierarchy of bounding surfaces formed from a draa carrying superimposed dunes. Both a and b contain an upper bounding surface which forms from the migration of another draa over the top of the cross-bedding left behind by a preceding dune.

& Clarke, 2020). However, outcrops exhibited no further evidence for a fluvial setting or fluvial associated facies (sensu Banham & Mountney, 2013). This includes the absence of erosive channels or their distinctive concentric fill (Fielding et al., 2012; Gibling, 2006), channel sandstones or conglomerates (Edgett et al., 2020; Newsom et al., 2016), and sigmoidal cross-bedding (Ghinassi et al., 2016). Additionally, first order bounding surfaces remain horizontal over large distances, which would be unlikely in a fluvial deposit (Brookfield, 1977; Kocurek, 1988). The ability to define the stratification types is distinctive to aeolian outcrops and is crucial in distinguishing cross-strata from a fluvial origin (Kocurek, 1991). The morphology of the cross-laminations observed in these outcrops reinforces their interpretation as pin-stripe laminations (sensu Fryberger & Schenk, 1988) and their classification as aeolian facies. Their uniform nature, and tendency to produce proud-weathering layers, are a distinctive features of aeolian sediments on Earth formed by wind ripples (Fryberger & Schenk, 1988). Moreover, no wet inter-dune features (such as microtopography, adhesion structures, aqueous ripples, or mud drapes; Kocurek, 1981; Table 1) were observed (Figure 16); therefore, post-depositional diagenetic features are the only evidence for water within these outcrops (Banham & Mountney, 2013).

Post-depositional, diagenetic features can be grouped as veins, fracture halos and concretions (Sun et al., 2019). The Stimson formation only exhibits smooth irregular shaped concretions, as seen in Figure 17e, unlike the Murray formation, which contains four concretion morphologies defined by Sun et al. (2019). Concretions typically form early during diagenesis, and the Murray formation was lithified long before the accumulation of the Stimson formation (Banham et al., 2025). Therefore, concretions formed within the Stimson formation are likely to have formed after those in the Murray formation. Mg-S-Ni-Cl-enriched fluids intruded both formations post-lithification (Sun et al., 2019), precipitating around a nucleation point and cementing surrounding grains (Banham et al., 2022). This facilitates growth of the concretion through adjacent pore spaces, forming concretions without interrupting surrounding sedimentary structures (Banham et al., 2022). Murray formation clasts are suggested as the nucleation points within the Stimson formation, having been ripped-up as dunes migrated across the unconformity, due to the abundance of concretions concentrated toward the base of the outcrops (Banham et al., 2022). Veins and alteration halos are differentiated by veins having sharp edges, whereas the fracture halo's edges are more diffuse. Veins in the Murray formation (Figure 17d) predominantly pre-date the Stimson emplacement and are interpreted as post-depositional sulfate-filled hydrofracture veins (Kronyak et al., 2019). Alteration halos are the areas of white bleaching observed (Figures 17a and 17b), formed from diagenesis of

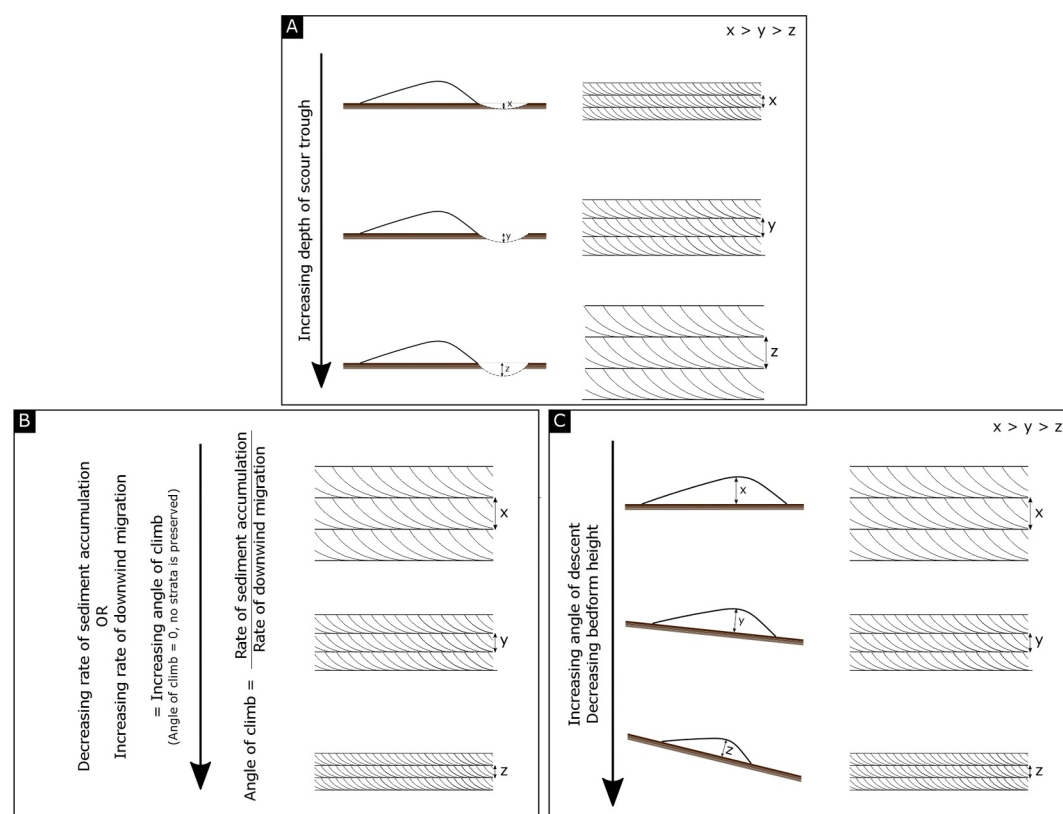


Figure 15. A series of diagrams outlining the possible explanations for the reduced cross-set thickness in the Stimson formation at Naukluft plateau in comparison to those measured at other Stimson outcrops by Banham et al. (2018, 2021, 2022). X, Y and Z are undefined values used for scale comparison; however, $X > Y > Z$ in terms of cross-bedding size. (a) The size of the dune scour trough is one factor determining the size of cross-bed preserved. The relationship between thickness of cross-set preserved and scour trough depth depends on the transport mechanism; however, in most cases, the larger the scour trough, the smaller the cross-sets preserved (Cardenas et al., 2023; Das et al., 2022). (b) Angle of climb is determined by the palaeosurface the dune is migrating across, notoriously hard to gauge from the stratigraphic record, but can be a big factor in producing small cross-sets. The steeper the incline, the smaller the preserved cross-sets (Mountney, 2012). (c) Angle of descent will decrease bedform height and hence the preserved set thickness (Reesink et al., 2015; Rubin & Hunter, 1982). This is relevant for the descent of the superimposed bedform down the draa lee as well as the migration of the draa itself. The dune migrating along a 0° incline will not preserve any cross-sets, instead it will produce a deflationary superset, but is used to illustrate the concept in this diagram.

surrounding rock as groundwater penetrated up through the Murray and Stimson formations, enriching these areas in silica and producing the color (Frydenvang et al., 2017; Kronyak et al., 2019; Sun et al., 2019; Yen et al., 2017). The processes forming these diagenetic features in the Stimson formation potentially occurred on a long temporal scale after deposition due to their cross-cutting relationships and variable morphology (Sun et al., 2019).

5. Discussion

5.1. Reconstruction of Dune Morphology and Sedimentary Processes

Aeolian processes were the dominant mode of sedimentation that formed the Naukluft plateau, as interpreted from the cross-strata, grain texture and outcrop architecture. Grainsize analysis revealed a bimodal grainsize distribution with two peaks: the first peak at corresponding to medium grained sandstone, and the second corresponding to coarse-grained sandstone. The medium sand fraction is typically associated with transport by saltation and reptation (Bagnold, 1941). The larger fraction of grains—greater than $700 \mu\text{m}$ —would have been transported predominantly by surface creep rather than saltation and reptation (Banham et al., 2022; Greeley et al., 1992). Cross-bedding observed across the plateau is predominantly compound cross-bedding, which is the preserved expression of migrating compound dunes (or draas). Compound cross-bedding is most common in the central-erg where there is sufficient sand supply to permit growth and formation of compound dunes.

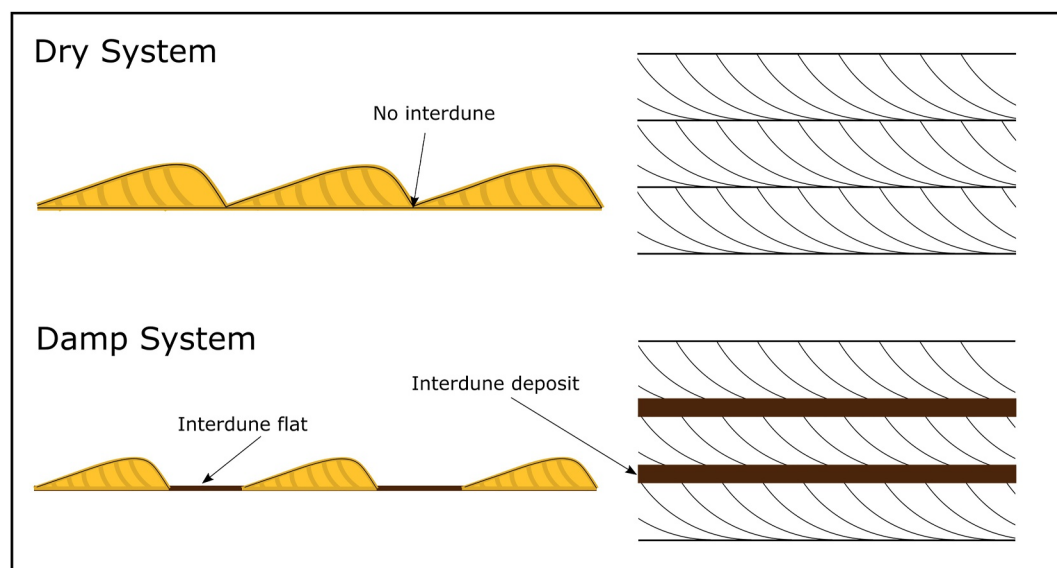


Figure 16. The dry system does not express any features which are an indication of surface water as described by Kocurek (1981); therefore, no interdune deposits are present in the preserved cross-bedding. A damp or wet interdune prevents dunes from immediately succeeding each other, depositing a characteristic layer between cross-sets. After Kocurek and Havholm, 1994.

Additionally, dune migration and growth during the growth phase tend to thwart preservation of the fore-erg as progressively large dunes have deeper scours, which remove the record of early stages of dune field construction (Banham et al., 2021). Porter (1986) suggests that cross-sets in the back-erg are smaller and contain coarser-

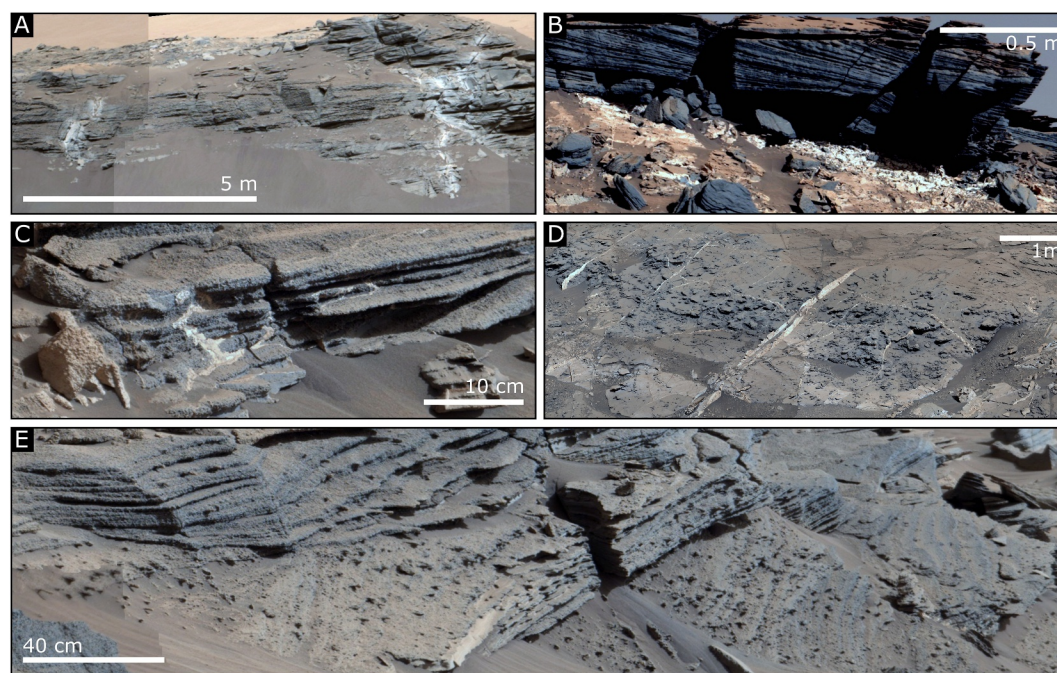


Figure 17. Magnified images from across the plateau of the various post-depositional diagenetic features in both the Murray and Stimson formation. (a) Alteration halos within the Stimson formation imaged on Sol 1381 (mcam006770). (b) Alteration halos tracing the unconformity within the Murray formation seen at the Sol 1272 (mcam005949) outcrop. (c) Veins present within the Stimson formation outcrop imaged on Sol 1348 (mcam006463). (d) Veins running through the Murray formation in the mosaic taken on Sol 1275 (mcam005976). Concretions are also observed in this image. (e) Concretions within the Sol 1348 (mcam006463) Stimson formation outcrop. Image credit: NASA/JPL-Caltech/MSSS/JR.

grained sand grains, which somewhat reflects strata preserved at the Naukluft plateau; however, the preservation potential of the back-erg is limited, particularly due to reduced sediment supply and reworking of any mobile sediment. These factors combined suggest that the strata exposed at Naukluft plateau is the preserved expression of the erg center of an ancient dune field (*sensu* Porter, 1986). Further, the Naukluft plateau may be an extension of the erg center exposed at the Murray buttes, owing to its proximity and spatial relations to the north of the Murray buttes (Banham et al., 2021).

There are no super-bounding surfaces identified within any Naukluft plateau outcrops (or indeed adjacent outcrops at Emerson plateau or the Murray buttes); therefore, the strata exposed here are unlikely to have experienced significant periods of deflation and erosion (*sensu* Blakey, 1988; Havholm & Kocurek, 1994). Instead, the succession likely accumulated relatively continuously. Neither wet nor damp interdune deposits (Figure 16), described by Kocurek (1981), are present within outcrops at the Naukluft plateau, including no hydrodynamically-controlled sediment accumulation (Havholm & Kocurek, 1994), indicating a dry aeolian depositional environment. The aridity of the primary depositional environment is independent of later groundwater related processes that occurred within the subsurface, as evidenced by the concretions, veins and alteration halos. The sediment transport direction is toward the north-northeast (toward 014°—north-northeast and is measured from cross-lamination dip-azimuths, Vector Magnitude 0.39). This palaeotransport direction supports a notional source area associated with the crater rim and walls to the south-west of the Stimson outcrops. This aligns with the interpretation of Bedford et al. (2020) that sediment at Naukluft was transported from the south-west toward the north-east (see Section 4.4.3.1 for more details).

Accurate estimates of the original dune height require knowledge of the primary dune's angle of climb, which is not easily determined from the Martian sedimentary record (Banham et al., 2021). Moreover, the proportion of the original dune preserved cannot be easily deciphered. However, following Lancaster (1988), who concluded that superimposed bedforms were approximately an order of magnitude smaller than primary dunes, and Banham et al. (2021, 2022), who assumed a dune's height was an order of magnitude larger than the preserved coset thickness, an estimate of the primary dune height can be made. Naukluft plateau cosets typically range between 1 and 2.5 m, and thus an estimate for the larger primary dunes would be in the region of ~20 m. Applying the same assumption to superimposed dunes, where the subsets averaged ~10 cm thickness at Naukluft, the corresponding superimposed dunes would have been ~1 m tall.

5.2. Reconstruction of the Dune Field Through Comparison to Other Stimson Formation Outcrops

All expressions of the Stimson formation thus far have exhibited common features: gray, cliff-forming, cross-bedded sandstone that unconformably overlie the lacustrine Murray formation. The Emerson plateau and the Ladder section of the Greenheugh pediment exhibit simple cross-bedding whereas the Murray buttes, Naukluft plateau and the Gleann Beag section of the Greenheugh pediment predominantly exhibit compound cross-bedding (Banham et al., 2018, 2021, 2022). With the grain size of each area (Table 2) and the migration direction of the broader erg toward the northeast (Bedford et al., 2020), we can estimate the architecture of the dune field. The features of the Stimson formation at the Naukluft plateau are best placed in the erg center; however, the compound cross-bedding suggests that it may record the transition from the fore-erg to a central setting. The lack of outcrops showing the lower Stimson formation cross-strata at Naukluft hinders confirmation of this interpretation (Figure 18).

5.3. Distribution of Concretions Across the Naukluft Plateau

The mosaics taken from across the plateau indicate a pattern of increasing concretions toward the base of the Stimson formation. The outcrops toward the periphery of the plateau, particularly the eastern and western outcrops, displayed more concretions than the central outcrops, likely due to the erosion and exposure of the base of the Stimson formation (Figure 19). The preferential distribution of concretions toward the base of the Stimson is also observed in the Emerson plateau and Murray buttes (Banham et al., 2018, 2021). Paired with the pattern of concretions increasing toward the outcrop base (Figure 11c), this suggests a distribution similar to that shown in Figure 19b. These diagenetic concretions require fluid events to form, so an up section decrease in porosity and permeability is suggested as the constraint on concretion distribution, leaving the uppermost outcrop sections with limited to no fluid exposure (Sun et al., 2019).

Table 2

A Comparison of the Measured Grain Size at Each of the Large Areas of Stimson Formation Outcrop, Inclusive of This Study

Stimson formation outcrop	Recorded grain size (geometric mean in μm)
Emerson plateau	406
Murray buttes	(No MAHLI observations made)
Greenheugh pediment	486
Naukluft plateau	482

Note. Measurements taken for the Emerson plateau, Murry buttes and Greenheugh pediment were by Banham et al. (2018, 2021, 2022) respectively.

It is inferred that water was unlikely to have originated from the surface, which was a hyperarid desert at the time (Banham et al., 2018). Concretions are most abundant at the base of the Stimson formation, decreasing in prevalence from the basal unconformity, with increasing stratigraphic height (Figure 19b). It is likely that the distribution of concretions reflects a stagnant or slow flowing perched water table (Figure 19a, sensu Banham et al., 2018, 2021). The impermeable Murray formation (Banham et al., 2025; Frydenvang et al., 2020) would have permitted a perched aquifer to form above the unconformity, and fluids escaping through or from the Murray formation would end up in the permeable Stimson formation sandstone.

The origin of the water is open to debate. Water could be derived from dewatering and hydrofracturing of the underlying lacustrine sediments (Banham et al., 2025) or be associated with an impact-generated hydrothermal

system (Newsome et al., 1996; Osinski et al., 2013). Fault systems formed by an impact or fracturing due to overpressure can act as fluid pathways (Osinski et al., 2013), enabling fluids to reach the higher strata. Hydrothermal systems do not last for extended time periods, potentially only several thousand years or so (Nau-mov, 2005). But whatever the origin of the water—hydrothermal, or otherwise—the system would have been active shortly after the deposition of the Stimson formation but before the erosion of the Stimson.

5.4. Conclusions

Studying the sedimentary architecture and texture of the Stimson formation at the Naukluft plateau, using data from the Curiosity rover has resulted in the following conclusions:

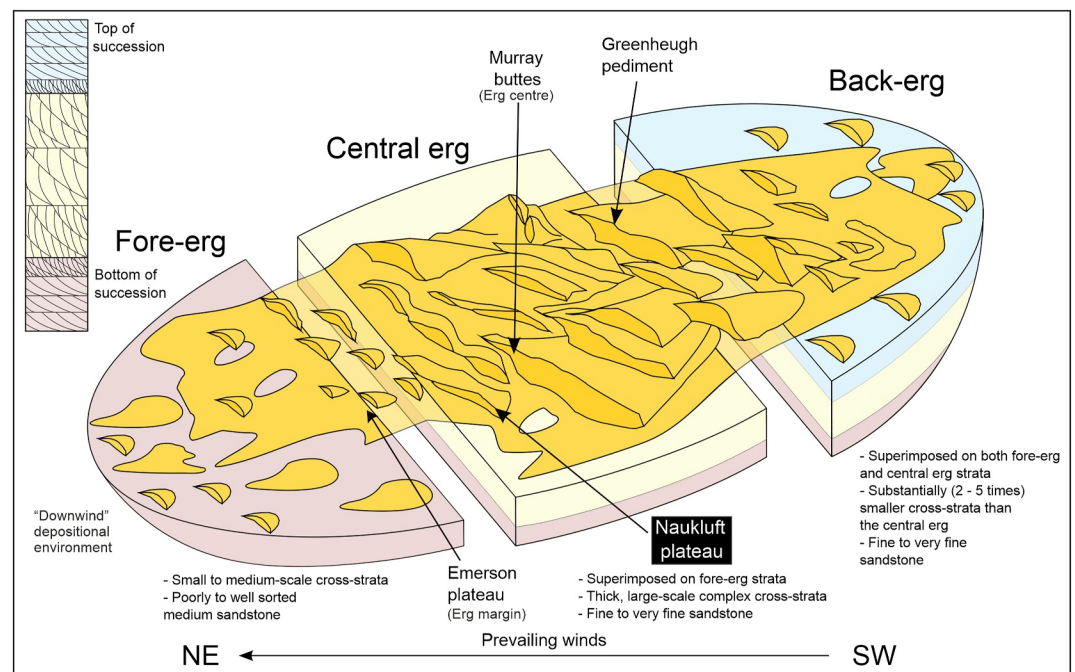


Figure 18. A reinterpretation of Porter's (1986) erg model. The erg deposits the fore-erg facies, then the central erg and finally the back-erg facies as it migrates in the direction of the prevailing wind, leaving each erg facies superimposed on top of one another. In the case of the Stimson formation in Gale crater, the prevailing wind was from the south-west to the north-east (as interpreted from the dip-azimuths recorded in the cross-strata at Naukluft plateau in this study, and at the Emerson plateau, Murray buttes and Greenheugh pediment by Banham et al. (2018, 2021, 2022) as well as via analysis of mineral sorting processes in aeolian transport by Bedford et al. (2020)). The erg from which the Stimson formation originates from has been lithified and subsequently eroded to expose the fore-erg and central erg boundary at the Greenheugh pediment (Banham et al., 2022), the central erg at the Murray buttes (Banham et al., 2021), the central-erg (close to the fore-erg) at the Naukluft plateau and the fore-erg margin at Emerson plateau (After Porter, 1986; Banham et al., 2018).

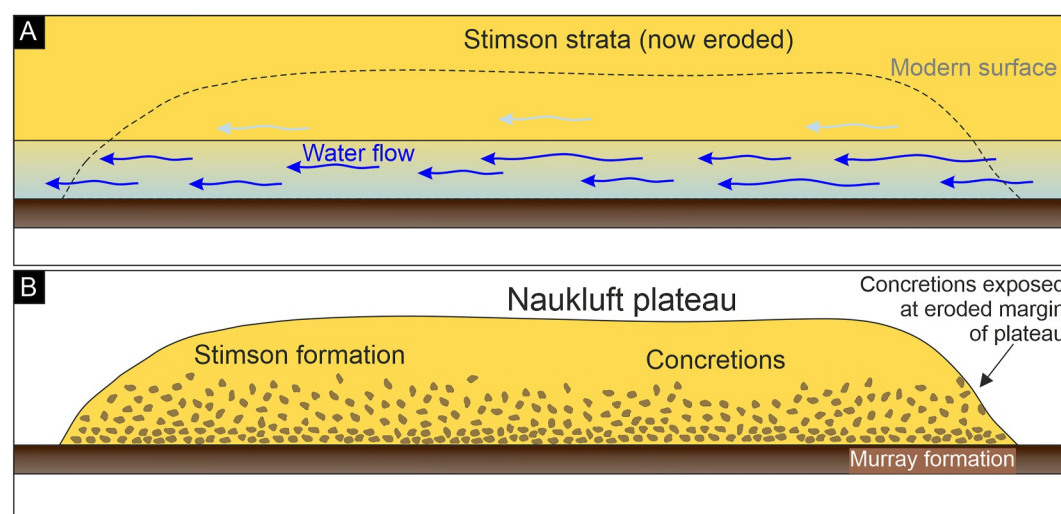


Figure 19. Distribution of concretions at the Naukluft plateau and interpreted through-flow of water to generate the observed distribution. (a) After the lithification of the Stimson formation, water percolated through the base of the Stimson formation, forming a “perched aquifer” on the impermeable Murray formation beneath the Base Siccar Point group unconformity. Water through-flow direction is arbitrary. (b) After erosion of the Naukluft plateau. This fluid flow leads to the observed distribution of concretions, where high concentrations of concretions are observed in the margins of the pediment. The central regions exhibit fewer concretions, as the basal portion of the Stimson is not exposed here.

1. The Stimson formation at the Naukluft plateau is a cliff-forming, dark gray, cross-bedded, sandstone deposited unconformably above the Murray formation. Grains have a geometric mean diameter of 482 μm , are moderate to well-rounded with moderate sphericity, and have a bimodal distribution. They are interpreted to be transported by both saltation and surface creep. Outcrops contain pin-stripe laminations, formed from wind-ripples, arranged to form compound cross-bedding. The dip-azimuth of the cross-laminations is oriented at 014°, indicating that the dunes migrated to the north.
2. All evidence supports aeolian depositional facies, apart from the cross-set scale, averaging 10 cm. Usually, this thickness depicts a fluvial depositional environment (Banham & Wakefield, 2015). If the dunes were migrating downslope, migrating at a low angle of climb, or if they underwent significant trough erosion, the preserved cross-strata would be significantly thinner (Mountney, 2012; Reesink et al., 2015).
3. Cross-bedding at Naukluft plateau contains cross-laminations and a hierarchy of bounding surfaces (Brookfield, 1977; Kocurek, 1981). First order bounding surfaces form from the scour trough of a migrating dune and can be traced for most of an outcrop. Second order surfaces, or subset bounding surfaces, represent erosional surfaces produced by migrating superimposed bedforms over a dune lee slope. Subset surfaces are bound between two first order surfaces that define a coset. Lastly, cross-laminations are the record of the superimposed bedform's lee slope at the time of deposition.
4. Cross-bedded sandstones at Emerson plateau (Banham et al., 2018), Murray buttes (Banham et al., 2021) and Greenheugh pediment (Banham et al., 2022) mirror features observed at the Naukluft plateau, and are therefore interpreted to have the same origin. Their combined characteristics, paired with the inferred sediment transport direction from Bedford et al. (2020), suggest a standard erg model (Porter, 1986) with prevailing winds to the north-east. The Naukluft plateau is thought to have been deposited within the erg center, or the fore-erg—central erg transition: a depositional environment forming cross-bedding smaller than the central erg (Porter, 1986).
5. A relict water table is recorded by the concretions concentrated at the base of the outcrops at the Naukluft plateau. The Stimson is absent of facies and architectural features which would indicate the water table impinging upon the depositional surface, which would result in a change of depositional style. The concretions post-date the accumulation of the strata, and are concentrated at the base of the outcrop, which suggests that water pooled in topographic lows on the unconformity surface, formed by the underlying and impermeable Murray formation.

In summary, this study conclusively shows that the Stimson formation at the Naukluft plateau is a dry aeolian deposit, analogous to the previous findings of Banham et al. (2018, 2021, 2022), with post-depositional diagenetic features formed in a perched aquifer.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data presented in this study are archived with the NASA Planetary Data System (PDS). Mastcam MAHLI and MARDI (MMM) images, along with engineering camera (Navcam & Hazcam) data are archived in the imaging portal (<https://pds-imaging.jpl.nasa.gov/volumes/msl.html>) and are readily accessible through the MSL Curiosity Analyst's Notebook (<https://an.rsl.wustl.edu/msl>). Mastcam data used in this study are publicly available via this database: Malin (2013). The location data used in this study are available via PDS - Places (2013). The images used can be found in a data table in Text S1 in Supporting Information S1 slide pack. Data (interpretations) generated during the course of this study are available in Text S1 in Supporting Information S1. Additional data related to this study are archived in the Zenodo data archive: Dean et al. (2025 [Dataset]), <https://doi.org/10.5281/zenodo.17806435>. This data repository contains grainsize measurements, dip & strike measurements, and a PowerPoint slide pack of images. Pro3D software details can be found at this website, <https://pro3d.space/>. A GitHub open-source release is available at <https://github.com/pro3d-space/PRO3D>.

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References

- Ahlbrandt, T. S. (1979). Textural parameters of eolian deposits. In E. D. McKee (Ed.), *A study of global sand seas* (pp. 21–51). United States Geological Survey Professional Paper.
- 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: Planets*, 111(E2), E02S02. <https://doi.org/10.1029/2005JE002462>
- Anderson, R. B., & Bell, J. F., III. (2010). Geologic mapping and Characterization of Gale crater and implications for its potential as a Mars Science Laboratory landing site. *Mars Journal*, 5, 76–128. <https://doi.org/10.1555/mars.2010.0004>
- Bagnold, R. A. (1941). The physics of blown sand and desert dunes (p. 265). <https://doi.org/10.1007/978-94-009-5682-7>
- Banham, S. G., Cosgrove, J. W., Paar, G., Gupta, S., Hughes, M. N., Grant, J. A., et al. (2025). A burial history of the sedimentary succession preserved in Aeolis Mons, as recorded by fracture networks at Maria Gordon notch, Gale crater, Mars. *Journal of Geophysical Research: Planets*, 130(7), e2024JE008843. <https://doi.org/10.1029/2024JE008843>
- 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), e2021JE007023. <https://doi.org/10.1029/2021JE007023>
- Banham, S. G., Gupta, S., Rubin, D. M., Edgett, K. S., Barnes, R., Van Beek, J., et al. (2021). A rock record of complex aeolian bedforms in a Hesperian desert landscape: The Stimson formation as exposed in the Murray buttes, Gale crater, Mars. *Journal of Geophysical Research: Planets*, 126(4), e2020JE006554. <https://doi.org/10.1029/2020JE006554>
- 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. (2013). Evolution of fluvial systems in salt-walled mini-basins: A review and new insights. *Sedimentary Geology*, 296, 142–166. <https://doi.org/10.1016/j.sedgeo.2013.08.010>
- Banham, S. G., Roberts, A. L., Gupta, S., Davis, J. M., Thompson, L. M., Rubin, D. M., et al. (2024). Ice? Salt? Pressure? Sediment deformation structures as evidence of late-stage shallow groundwater in Gale crater, Mars. *Geology*, 52(7), 492–496. <https://doi.org/10.1130/G51849.1>
- Banham, S. G., & Wakefield, O. (2015). BSRG core workshop: Aeolian-fluvial dryland systems. Retrieved from <https://nora.nerc.ac.uk/id/eprint/516995>
- Barnes, R., Gupta, S., Traxler, C., Ortner, T., Bauer, A., Hesina, G., et al. (2018). Geological analysis of Martian rover-derived digital outcrop models using the 3D visualization tool, planetary robotics 3-D viewer - Pro3D. *Earth and Space Science*, 5(7), 285–307. <https://doi.org/10.1002/2018EA000374>
- Bedford, C. C., Banham, S. G., Bridges, J. C., Forni, O., Cousin, A., Bowden, D., et al. (2022). An insight into ancient aeolian processes and post-Noachian aqueous alteration in Gale crater, Mars, using ChemCam geochemical data from the Greenheugh capping unit. *Journal of Geophysical Research: Planets*, 127(9), e2021JE007100. <https://doi.org/10.1029/2021JE007100>
- Bedford, C. C., Schwenzer, S. P., Bridges, J. C., Banham, S., Wiens, R. C., Gasnault, O., et al. (2020). Geochemical variation in the Stimson formation of Gale crater: Provenance, mineral sorting, and a comparison with modern Martian dunes. *Icarus*, 341, 113622. <https://doi.org/10.1016/j.icarus.2020.113622>
- Bell, J. F., III., Godber, A., McNair, S., Caplinger, M. A., Maki, J. N., Lemmon, M. T., et al. (2017). The Mars Science Laboratory curiosity 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>
- Bennett, K. A., Fox, V. K., Bryk, A., Dietrich, W., Fedo, C., Edgar, L., et al. (2023). The Curiosity rover's exploration of Glen Torridon, Gale crater, Mars: An overview of the campaign and scientific results. *Journal of Geophysical Research: Planets*, 128(1), e2022JE007185. <https://doi.org/10.1029/2022JE007185>

- 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:stsaao>2.3.co;2](https://doi.org/10.1130/0091-7613(1988)016<0483:stsaao>2.3.co;2)
- Blott, S., & Pye, K. (2001). GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26(11), 1237–1248. <https://doi.org/10.1002/esp.261>
- Brookfield, M. E. (1977). The origin of bounding surfaces in ancient aeolian sandstones. *Sedimentology*, 24(3), 303–332. <https://doi.org/10.1111/j.1365-3091.1977.tb00126.x>
- Calef, F. J., Dietrich, W. E., Edgar, L., Farmer, J., Fraeman, A., Grotzinger, J., et al. (2016). Geologic mapping of the Mars science laboratory landing ellipse (p. 7040).
- Calef, F. J., & Parker, T. (2016a). *Mars MSL gale merged DEM 1m*. PDS Annex, U.S. Geological Survey.
- Calef, F. J., & Parker, T. (2016b). *MSL gale merged orthophoto mosaic*. MSL Team, PDS Annex, U.S. Geological Survey. Retrieved from http://bit.ly/MSL_BaseMap
- 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>
- Cardenas, B. T., Stacey, K., & Baran, Z. J. (2023). Relationships between fluvial dune cross-set thickness, planview width, and trough geometry. *Geology*, 51(12), 1163–1167. <https://doi.org/10.1130/G51540.1>
- Carr, M. H., & Head, J. W., III. (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>
- Colombera, L., Reesink, A. J. H., Duller, R. A., Jeavons, V. A., & Mountney, N. P. (2024). The thickness variability of fluvial cross-strata as a record of dune disequilibrium and palaeohydrology proxy: A test against channel deposits. *Sedimentology*, 71(2), 590–618. <https://doi.org/10.1111/sed.13147>
- Cross, S., Pettigrew, R. P., Priddy, C. L., Zuchuat, V., Dodd, T. J. H., Mitten, A. J., & Clarke, S. M. (2023). The sedimentological expression of transgression–regression cycles upon aeolian–marine margins. *The Depositional Record*, 9(2), 335–362. <https://doi.org/10.1002/dep2.225>
- Das, D., Ganti, V., Bradley, R., Venditti, J., Reesink, A., & Parsons, D. R. (2022). The influence of transport stage on preserved fluvial cross strata. *Geophysical Research Letters*, 49(18), e2022GL099808. <https://doi.org/10.1029/2022GL099808>
- Davis, J. M., Dietrich, W. E., Gupta, S., Bryk, A. B., Banham, S. G., Wilson, S., et al. (2023). The Gediz Vallis inverted channel: Evidence for late-stage flow in Gale crater, Mars? In *Paper presented at lunar and planetary science conference*.
- Dean, A. E., Banham, S. G., Paar, G., Gupta, S., Davis, J. M., & Vasavada, A. (2025). Sedimentary architecture of the Stimson formation at the Naukluft plateau, Gale crater, Mars., edited, Zenodo, EU open research repository [Dataset]. <https://doi.org/10.5281/zenodo.17806435>
- De Hon, R. A., Barlow, N. G., Reagan, M. K., Bettis, E. A., Iii, Foster, C. T., Jr., Gulick, V. C., et al. (2001). Observation of the geology and geomorphology of the 1999 Marsokhod test site. *Journal of Geophysical Research*, 106(E4), 7665–7682. <https://doi.org/10.1029/1999JE001167>
- Dromart, G., Le Deit, L., Rapin, W., Gasnault, O., Le Moulic, 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>
- Eastwood, E. N., Kocurek, G., Mohrig, D., & Swanson, T. (2012). Methodology for reconstructing wind direction, wind speed and duration of wind events from aeolian cross-strata. *Journal of Geophysical Research*, 117(F3). <https://doi.org/10.1029/2012JF002368>
- Edgar, L., 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 *LPSC* (p. 1016). Retrieved from <https://www.hou.usra.edu/meetings/lpsc2024/pdf/1016.pdf>
- Edgar, L. A., Gupta, S., Rubin, D. M., Lewis, K. W., Kocurek, G. A., Anderson, R. B., et al. (2018). Shaler: In situ analysis of a fluvial sedimentary deposit on Mars. *Sedimentology*, 65(1), 96–122. <https://doi.org/10.1111/sed.12370>
- Edgett, K. S., Banham, S. G., Bennett, K. A., Edgar, L. A., Edwards, C. S., Fairn, A. G., et al. (2020). Extraformational sediment recycling on Mars. *Geosphere*, 16(6), 1508–1537. <https://doi.org/10.1130/GES02244.1>
- 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>
- 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), e2022JE007408. <https://doi.org/10.1029/2022JE007408>
- Fielding, C. R., Ashworth, P. J., Best, J. L., Prokocki, E. W., & Smith, G. H. S. (2012). Tributary, distributary and other fluvial patterns: What really represents the norm in the Continental rock record? *Sedimentary Geology*, 261, 15–32. <https://doi.org/10.1016/j.sedgeo.2012.03.004>
- Folk, R. L. (1980). *Petrology of sedimentary rocks*. Hemphill Publishing Company. Retrieved from <http://hdl.handle.net/2152/22930>
- Folk, R. L. (1978). Angularity and Silica Coatings of Simpson desert sand grains, Northern Territory, Australia. *Journal of Sedimentary Research*, 48(2), 611–624. <https://doi.org/10.1306/212F74E6-2B24-11D7-8648000102C1865D>
- 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., & 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)
- Frydenvang, J., Gasda, P. J., Hurowitz, J. A., Grotzinger, J. P., Wiens, R. C., Newsom, H. E., et al. (2017). Diagenetic silica enrichment and late-stage groundwater activity in Gale crater, Mars. *Geophysical Research Letters*, 44(10), 4716–4724. <https://doi.org/10.1002/2017GL073323>
- Frydenvang, J., Mangold, N., Wiens, R. C., Fraeman, A. A., Edgar, L. A., Fedo, C. M., et al. (2020). The chemostratigraphy of the Murray Formation and role of diagenesis at Vera Rubin Ridge in Gale crater, Mars, as observed by the ChemCam instrument. *Journal of Geophysical Research: Planets*, 125(9), e2019JE006320. <https://doi.org/10.1029/2019JE006320>
- Garzanti, E. (2017). The maturity myth in sedimentology and provenance analysis. *Journal of Sedimentary Research*, 87(4), 353–365. <https://doi.org/10.2110/jsr.2017.17>
- Ghinassi, M., Ielpi, A., Aldinucci, M., & Fustic, M. (2016). Downstream-migrating fluvial point bars in the rock record. *Sedimentary Geology*, 334, 66–96. <https://doi.org/10.1016/j.sedgeo.2016.01.005>
- 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), 731–770. <https://doi.org/10.2110/jsr.2006.060>

- Greeley, R., Arvidson, R. E., Elachi, C., Geringer, M. A., Plaut, J. J., Saunders, R. S., et al. (1992). Aeolian features on Venus - Preliminary Magellan results. *Journal of Geophysical Research: Planets*, 97(E8), 13319–13345. <https://doi.org/10.1029/92je00980>
- Greeley, R., & Iversen, J. D. (1985). *Wind as a geological process: On Earth, Mars, Venus and Titan*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511573071>
- Greeley, R., & Iversen, J. D. (1987). Measurements of wind friction speeds over lava surfaces and assessment of sediment transport. *Geophysical Research Letters*, 14(9), 925–928. <https://doi.org/10.1029/GL014i009p00925>
- Grotzinger, J. P., Crisp, J. A., Vasavada, A. R., & Team, M. S. L. S. (2015). Curiosity's mission of exploration at Gale crater, Mars. *Elements*, 11(1), 19–26. <https://doi.org/10.2113/gselements.11.1.19>
- Grotzinger, J. P., Gupta, S., Malin, M. C., Rubin, D. M., Schieber, J., Siebach, K., et al. (2015). Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. *Science*, 350(6257), aac7575. <https://doi.org/10.1126/science.aac7575>
- Grotzinger, J. P., & Milliken, R. E. (2012). The sedimentary rock record of Mars: Distribution, origins, and global stratigraphy. *Society for Sedimentary Geology*, 12, 1–48. <https://doi.org/10.2110/pec.12.102.0001>
- Gwizd, S., Fedo, C., Grotzinger, J., Banham, S., Rivera-Hernandez, F., Stack, K. M., et al. (2022). Sedimentological and geochemical perspectives on a Marginal lake environment recorded in the Hartmann's Valley and Karasburg members of the Murray formation, Gale crater, Mars. *Journal of Geophysical Research: Planets*, 127(8), e2022JE007280. <https://doi.org/10.1029/2022JE007280>
- Gwizd, S., Fedo, C., Grotzinger, J., Edgett, K., Rivera-Hernandez, F., & Gupta, S. (2020). Transition from a lacustrine margin to a lacustrine Basin in Gale crater, Mars: The Hartmann's Valley and Karasburg members of the Murray formation. In *Paper presented at Lunar and Planetary science conference*. Retrieved from <https://www.hou.usra.edu/meetings/lpsc2020/pdf/2719.pdf>
- 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>
- Hunter, R. E. (1977). Terminology of cross-stratified sedimentary layers and climbing-ripple structures. *Journal of Sedimentary Research*, 47(2), 697–706. <https://doi.org/10.1306/212F7225-2B24-11D7-8648000102C1865D>
- Kocurek, G. (1981). Significance of interdune deposits and bounding surfaces in aeolian dune sands. *Sedimentology*, 28(6), 753–780. <https://doi.org/10.1111/j.1365-3091.1981.tb01941.x>
- Kocurek, G. (1988). First-order and super bounding surfaces in eolian sequences - Bounding surfaces revisited. *Sedimentary Geology*, 56(1–4), 193–206. [https://doi.org/10.1016/0037-0738\(88\)90054-1](https://doi.org/10.1016/0037-0738(88)90054-1)
- Kocurek, G. (1991). Interpretation of ancient eolian sand dunes. *Annual Review of Earth and Planetary Sciences*, 19(1), 43–75. <https://doi.org/10.1146/annurev.ea.19.050191.000355>
- 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>
- Kronyak, R. E., Kah, L. C., Miklusicak, N. B., Edgett, K. S., Sun, V. Z., Bryk, A. B., & Williams, R. M. E. (2019). Extensive polygonal fracture network in Siccar Point group strata: Fracture mechanisms and implications for fluid circulation in Gale crater, Mars. *Journal of Geophysical Research: Planets*, 124(10), 2613–2634. <https://doi.org/10.1029/2019je006125>
- Lancaster, N. (1982). Linear dunes. *Progress in Physical Geography*, 6(4), 475–504. <https://doi.org/10.1177/03091338200600401>
- Lancaster, N. (1988). Controls of eolian dune size and spacing. *Geologica*, 16(11), 972–975. [https://doi.org/10.1130/0091-7613\(1988\)016<0972:coedsa>2.3.co;2](https://doi.org/10.1130/0091-7613(1988)016<0972:coedsa>2.3.co;2)
- Lancaster, N. (1995). *Geomorphology of desert dunes*. Routledge. <https://doi.org/10.1017/9781108355568>
- Lapotre, M. G. A., Ewing, R. C., & Lamb, M. P. (2021). An evolving understanding of enigmatic large ripples on Mars. *Journal of Geophysical Research: Planets*, 126(2), e2020JE006729. <https://doi.org/10.1029/2020JE006729>
- 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>
- Lopez, G. I. (2017). Grain size analysis. In A. S. Gilbert (Ed.), *Encyclopedia of geoarchaeology* (pp. 341–348). Springer. https://doi.org/10.1007/978-1-4020-4409-0_18
- 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/s11214-012-9882-4>
- Malin, M. C. (2013). *MSL Mars Mast Camera RDR V1.0, NASA Planetary Data System, MSL-M-MASTCAM-4-RDR-IMG-V1.0, 2013*. NASA Planetary Data System. <https://doi.org/10.17189/1520328>
- 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., Tony Ghaemi, F., 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>
- Marshall, J. R., Borucki, J., & Bratton, C. (1999). Aeolian sand transport in the planetary context: Respective roles of aerodynamic and bed-dilatancy thresholds. In *Studies of mineralogical and textural properties of Martian soil: An exobiological perspective* (Vol. 18). Retrieved from <https://ntrs.nasa.gov/citations/20000025361>
- 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: Planets*, 112(E5), E002605. <https://doi.org/10.1029/2005je002605>
- McLaren, P., & Bowles, D. (1985). The effects of sediment transport on grain-size distributions. *Journal of Sedimentary Research*, 55(4), 457–470. <https://doi.org/10.1306/212F86FC-2B24-11D7-8648000102C1865D>
- MEPAG. (2020). Mars scientific goals, objectives, investigations, and priorities: 2020 Rep., Mars Exploration Program Analysis Group. Retrieved from <https://mepag.jpl.nasa.gov/reports.cfm>
- 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>
- Moore, H. J. (1971). Geologic interpretation of lunar data. *Earth-Science Reviews*, 7(1), 5–33. [https://doi.org/10.1016/0012-8252\(71\)90002-X](https://doi.org/10.1016/0012-8252(71)90002-X)
- Mountney, N. P. (2006). Periodic accumulation and destruction of aeolian erg sequences in the Permian Cedar Mesa Sandstone, White Canyon, southern Utah, USA. *Sedimentology*, 53(4), 789–823. <https://doi.org/10.1111/j.1365-3091.2006.00793.x>
- Mountney, N. P. (2012). A stratigraphic model to account for complexity in Aeolian dune and interdune successions. *Sedimentology*, 59(3), 964–989. <https://doi.org/10.1111/j.1365-3091.2011.01287.x>
- Naumov, M. V. (2005). Principal features of impact-generated hydrothermal circulation systems: Mineralogical and geochemical evidence. *Geofluids*, 5(3), 165–184. <https://doi.org/10.1111/j.1468-8123.2005.00092.x>

- Newsom, H., Belgacem, I., Jackson, R., Ha, B., Vaci, Z., Wiens, R., et al. (2016). The materials at an unconformity between the Murray and Stimson formations at Marias Pass, Gale crater, Mars. In *Lunar and planetary science conference* (p. 2397). Retrieved from <https://hal.science/hal-02902911v1>
- Newsom, H. E., Brittelle, G. E., Hibbitts, C. A., Crossey, L. J., & Kudo, A. M. (1996). Impact Crater Lakes on Mars. *Journal of Geophysical Research*, 101(E6), 14951–14955. <https://doi.org/10.1029/96JE01139>
- Osinski, G. R., Tornabene, L. L., Banerjee, N. R., Cockell, C. S., Flemming, R., Izawa, M. R. M., et al. (2013). Impact-generated hydrothermal systems on Earth and Mars. *Icarus*, 224(2), 347–363. <https://doi.org/10.1016/j.icarus.2012.08.030>
- Paar, G., & Almer, A. (1994). Fast hierarchical stereo reconstruction. In *Optical 3D measurement techniques II: Applications in inspection, quality control, and robotics* (pp. 284–291). International Society for Optics and Photonics.
- Paar, G., Huber, B., Gupta, S., Barnes, R., Traxler, C., & Ortner, T. (2017). Planetary rover Vision processing and visualization: PRoViP and PRo3D. In *Proc. Global space exploration conference*.
- Paar, G., Ortner, T., Tate, C., Deen, R. G., Abercrombie, P., Vona, M., et al. (2023). Three-dimensional data preparation and immersive mission-spanning visualization and analysis of Mars 2020 Mastcam-Z stereo image sequences. *Earth and Space Science*, 10(3), e2022EA002532. <https://doi.org/10.1029/2022EA002532>
- Paar, G., Ortner, T., Traxler, C., Barnes, R., Balme, M., Schroeder, C., et al. (2022). Preparing 3D vision & visualization for ExoMars. *Paper presented at symposium on advanced space technologies in robotics and automation*. ESA/ESTEC. Retrieved from <https://www.vrvvis.at/publications/PB-VRVis-2022-017>
- Paar, G., Waugh, L., Barnes, D., Pajdla, T., Woods, M., Graf, H.-R., et al. (2012). Integrated field testing of planetary robotics vision processing: The PRoViG campaign in Tenerife 2011. *Paper presented at intelligent robots and computer vision XXIX: Algorithms and techniques* (pp. 224–241). International Society for Optics and Photonics. <https://doi.org/10.1117/12.906410>
- PDS - Places. (2013). Mars Science Laboratory (MSL) position localization and attitude correction estimate storage (PLACES) archive [Dataset]. *MSL-M-MASTCAM-2-EDR-IMG-V1.0*, edited, JPL-NASA, Planetary Data System. Retrieved from https://planetarydata.jpl.nasa.gov/img/doc/ta/msl/msl_places/
- Porter, M. L. (1986). Sedimentary record of erg migration. *Geologica*, 14(6), 497–500. [https://doi.org/10.1130/0091-7613\(1986\)14<497:sroem>2.0.co;2](https://doi.org/10.1130/0091-7613(1986)14<497:sroem>2.0.co;2)
- Powers, M. C. (1953). A new roundness scale for sedimentary particles. *Journal of Sedimentary Research*, 23(2), 117–119. <https://doi.org/10.1306/D4269567-2B26-11D7-8648000102C1865D>
- Preston, S. (2023). *Differences between modern and ancient martian grain size distributions may reveal different paleoatmospheric conditions and provenance*. Rice University.
- Preston, S. L., Siebach, K. L., Lapotre, M. G. A., & Banham, S. G. (2024). Grain size measurements of the eolian Stimson formation, Gale crater, Mars and implications for sand provenance and paleoatmospheric conditions. *Journal of Geophysical Research: Planets*, 129(11), e2024JE008369. <https://doi.org/10.1029/2024JE008369>
- 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>
- Pye, K., & Tsoar, H. (2008). *Aeolian sand and sand dunes*. Springer. <https://doi.org/10.1007/978-3-540-85910-9>
- 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. *Geologica*, 49(7), 842–846. <https://doi.org/10.1130/G48519.1>
- Ray, R. G. (1960). Aerial photographs in geologic interpretation and mapping. *US Geological Survey*. Retrieved from <https://pubs.usgs.gov/pp/0373/report.pdf>
- Reesink, A. J. H., Van den Berg, J. H., Parsons, D. R., Amsler, M. L., Best, J. L., Hardy, R. J., et al. (2015). Extremes in dune preservation: Controls on the completeness of fluvial deposits. *Earth-Science Reviews*, 150, 652–665. <https://doi.org/10.1016/j.earscirev.2015.09.008>
- 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(5), e2024JE008680. <https://doi.org/10.1029/2024JE008680>
- 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>
- Rubin, D. M. (1987). Cross-bedding, bedforms, and paleocurrents. *SEPM Concepts in sedimentology and paleontology*, 1, 187p. <https://doi.org/10.2110/csp.87.01>
- Rubin, D. M., & Hunter, R. E. (1983a). Interpreting cyclic crossbedding, with an example from the Navajo sandstone. In M. E. Brookfield & T. S. Ahlbrandt (Eds.), *Eolian sediments and processes* (pp. 429–454). Elsevier. [https://doi.org/10.1016/S0070-4571\(08\)70808-2](https://doi.org/10.1016/S0070-4571(08)70808-2)
- Rubin, D. M., & Hunter, R. E. (1983b). Reconstructing bedform assemblages from compound crossbedding. In *Developments in sedimentology* (pp. 407–427). [https://doi.org/10.1016/S0070-4571\(08\)70807-0](https://doi.org/10.1016/S0070-4571(08)70807-0)
- Rubin, D. M., & Hunter, R. E. (1987). Bedform alignment in directionally varying flows. *Science*, 237(4812), 276–278. <https://doi.org/10.1126/science.237.4812.276>
- Rudolph, A., Horgan, B., Bennett, K., Weitz, C., Sheppard, R., Banham, S. G., et al. (2024). An orbital comparison of a late mantling unit on Aeolis Mons with other erosion-resistant strata explored by MSL in Gale crater, Mars. *Journal of Geophysical Research: Planets*, 129(8), e2023JE008242. <https://doi.org/10.1029/2023JE008242>
- Sharp, R. P. (1963). Wind ripples. *The Journal of Geology*, 71(5), 617–636. <https://doi.org/10.1086/626936>
- Siebach, K., McLennan, S., & Fedo, C. (2017). Geochemistry of the Stimson Sandstone, Gale crater, Mars. In *Paper presented at lunar and planetary science conference, Houston*.
- Stack, K. M., Ives, L. R. W., Gupta, S., Lamb, M. P., Tebolt, M., Caravaca, G., et al. (2024). Sedimentology and stratigraphy of the shenandoah Formation, Western fan, jezero crater, Mars. *Journal of Geophysical Research: Planets*, 129(2), e2023JE008187. <https://doi.org/10.1029/2023JE008187>
- 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>
- Stein, N. T., Quinn, D. P., Grotzinger, J. P., Fedo, C., Ehlmann, B. L., Stack, K. M., et al. (2020). Regional structural orientation of the Mount Sharp Group revealed by in situ dip measurements and stratigraphic correlations on the Vera Rubin Ridge. *Journal of Geophysical Research: Planets*, 125(5), e2019JE006298. <https://doi.org/10.1029/2019JE006298>
- Sullivan, R., Kok, J. F., Katra, I., & Yizhaq, H. (2020). A broad continuum of Aeolian impact ripple morphologies on Mars is enabled by low wind dynamic pressures. *Journal of Geophysical Research: Planets*, 125(10), e2020JE006485. <https://doi.org/10.1029/2020JE006485>
- Sun, V. Z., Stack, K. M., Kah, L. C., Thompson, L., Fischer, W., Williams, A. J., et al. (2019). Late-stage diagenetic concretions in the Murray formation, Gale crater, Mars. *Icarus*, 321, 866–890. <https://doi.org/10.1016/j.icarus.2018.12.030>

- Tanaka, K. L., Skinner, J. A., Jr., Dohm, J. M., Irwin, R. P., III, Kolb, E. J., Fortezzo, C. M., et al. (2014). Geologic map of Mars. *US Geological Survey*. <https://doi.org/10.3133/sim3292>
- Thomson, B. J., Bridges, N. T., Milliken, R., Baldridge, 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>
- Traxler, C., Ortner, T., Hesina, G., Barnes, R., Gupta, S., Paar, G., et al. (2018). The PRoViDE Framework: Accurate 3D geological models for virtual exploration of the Martian surface from rover and orbital imagery. In A. Bistacchi, L. Jorda, M. Massironi, & S. Viseur (Eds.), *3D digital geological models: From terrestrial outcrops to planetary surfaces*. John Wiley & Sons. <https://doi.org/10.1002/9781119313922.ch3>
- Traxler, C. H., Ortner, T., Hesina, G., Barnes, R., Gupta, S., Paar, G., et al. (2022). The PRoViDE framework: Accurate 3D geological models for virtual exploration of the Martian surface from Rover and orbital imagery. In *3D digital geological models: From terrestrial outcrops to planetary surfaces* (pp. 33–55). <https://doi.org/10.1002/9781119313922.ch3>
- Twenhofel, W. H. (1945). The rounding of sand grains. *Journal of Sedimentary Research*, 15(2), 59–71. <https://doi.org/10.1306/d4269224-2b26-11d7-8648000102c1865d>
- Warner, N., Silverman, M., Samuels, J., DeFlores, L., Sengstacken, A., Maki, J., et al. (2016). The Mars science laboratory remote sensing mast. In *2016 IEEE aerospace conference* (pp. 1–9). <https://doi.org/10.1109/AERO.2016.7500554>
- 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), e2022JE007293. <https://doi.org/10.1029/2022JE007293>
- Wentworth, C. K. (1922). A Scale of grade and class terms for clastic sediments. *The Journal of Geology*, 30(5), 377–392. <https://doi.org/10.1086/622910>
- Wentworth, C. K. (1933). Fundamental limits to the sizes of clastic grains. *Science*, 77(2009), 633–634. <https://doi.org/10.1126/science.77.2009.633>
- 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>
- Yen, A. S., Ming, D. W., Vaniman, D. T., Gellert, R., Blake, D. F., Morris, R. V., et al. (2017). Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale crater, Mars. *Earth and Planetary Science Letters*, 471, 186–198. <https://doi.org/10.1016/j.epsl.2017.04.033>