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Key Points:

- Compound cross-bedding at the Murray buttes record the migration of oblique aeolian dunes.
- Large dunes (draas) migrated to the NNW, while superimposed dunes migrated NE. The bulk sediment transport direction was broadly toward the north
- The Stimson formation observed at the Murray buttes shares a common depositional architecture seen in other Stimson formation outcrop observed elsewhere on the traverse

Supporting Information:

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

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A Rock Record of Complex Aeolian Bedforms in a Hesperian Desert Landscape: The Stimson Formation as Exposed in the Murray Buttes, Gale Crater, Mars

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Abstract Lithified aeolian strata encode information about ancient planetary surface processes and the climate during deposition. Decoding these strata provides insight regarding past sediment transport processes, bedform kinematics, depositional landscape, and the prevailing climate. Deciphering these signatures requires a detailed analysis of sedimentary architecture to reconstruct dune morphology, motion, and the conditions that enabled their formation. Here, we show that a distinct sandstone unit exposed in the foothills of Mount Sharp, Gale crater, Mars, records the preserved expression of compound aeolian bedforms that accumulated in a large dune field. Analysis of Mastcam images of the Stimson formation shows that it consists of cross-stratified sandstone beds separated by a hierarchy of erosive bounding surfaces formed during dune migration. The presence of two orders of surfaces with distinct geometrical relations reveals that the Stimson-era landscape consisted of large dunes (draas) with smaller, superimposed dunes migrating across their lee slopes. Analysis of cross-lamination and subset bounding surface geometries indicate a complex wind regime that transported sediment toward the north, constructing oblique dunes. This dune field was a direct product of the regional climate and the surface processes active in Gale crater during the fraction of the Hesperian Period recorded by the Stimson formation. The environment was arid, supporting a large aeolian dune field; this setting contrasts with earlier humid depositional episodes, recorded by the lacustrine sediments of the Murray formation (also Hesperian). Such fine-scale reconstruction of landscapes on the ancient surface of Mars is important to understanding the planet's past climate and habitability.

Plain Language Summary Sedimentary rocks formed from sediments transported and deposited by the wind provide valuable information about the ancient environment, such as climate, wind direction, and the types of desert landforms that were present. This study focuses on the windblown sediments, now sandstone, imaged using the Mastcam instrument onboard the Mars Science Laboratory rover, Curiosity, at the Murray buttes inside Gale crater, between the 1383rd and 1455th Martian days (sols) of the mission. Analysis of the sedimentary structures in images shows that the Stimson formation at the Murray buttes was deposited by the wind in the form of compound sand dunes. These were large dunes with smaller dunes migrating across their surfaces. Analysis of the sedimentary structures generated by the complex interaction of these two scales of dune indicates that the large dunes migrated north, and that the smaller superimposed dunes migrated across the faces of the large dunes toward the northeast. The presence of large, wind-driven dunes indicates that the region was extremely arid, and that—at the time the Stimson dune field existed—the interior of Gale crater was devoid of surface water, unlike the setting recorded by the older, underlying lake sediments of the Murray formation.



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1. Introduction

Ancient sand dune formed by wind transport and deposition is common in Earth's rock record (Rodríguez-López et al., 2014). By studying the sedimentary texture and internal stratigraphy of these rocks, we can discern the physical processes that shaped the ancient dunes, reconstruct the morphology and motion of the bedforms, make inferences about the dynamic behavior of dunes, and place quantitative constraints on the setting and dune field landscape (Kocurek, 1991; Rubin & Hunter, 1982). Moreover, we can draw insight into the ancient local and regional sediment budgets, and prevailing climate and climate fluctuations (Kocurek & Lancaster, 1999; Mountney, 2006; Rubin & Hunter, 1987).

Reconstructing what the ancient Martian landscape looked like and the surface processes that shaped it informs us about the planet's geological evolution and paleoclimate history. Since 1999, exploration by Mars orbiters (Malin & Edgett, 2000; Milliken et al., 2014; Sarkar et al., 2019) and rovers (Banham et al., 2018; Dromart et al., 2021; Edgar et al., 2012; Grotzinger et al., 2005; Hayes et al., 2011; Metz et al., 2009; Squyres et al., 2009) has revealed evidence for ancient aeolian strata exposed at the planet's surface, enabling the study of surface processes in the distant past using the assiduous application of knowledge developed through field studies on Earth. The purpose of this contribution is to reconstruct the morphology and land-scape from a record of complex aeolian bedform assemblages in rocks exposed in Gale crater, Mars, using images of outcrops of a distinctive stratigraphic unit, informally known as the Stimson formation.

The migration of wind-blown sand dunes is recorded in clastic rocks as a distinctive sedimentary structure termed cross-stratification (Bagnold, 1941; McKee & Weir, 1953; Reiche, 1938). Cross-strata are common components of sedimentary rocks and provide a key record of ancient morphodynamics of bedforms in a range of paleoenvironments: these can be aeolian, fluvial, or marine (Bridge & Best, 1997; Jerolmack & Mohrig, 2005; Kocurek, 1991; Kocurek & Dott, 1981; Rubin, 1987a; Rubin & Hunter, 1982; Smith, 1986). In particular, cross-strata, the most fundamental elements of the depositional record of aeolian dune fields, have been widely used on Earth to reconstruct the bedform morphologies that were present and the processes that occurred in ancient dune fields (Blakey et al., 1988; Hunter, 1977; Rubin & Hunter, 1983). Modern aeolian sediments—sand and dust deposits—are ubiquitous on the surface of Mars (Bourke et al., 2008, 2019; Bridges et al., 2017; Christensen, 1986; Cutts & Smith, 1973; Ewing et al., 2017; Fenton et al., 2019; Hayes et al., 2011; Sullivan et al., 2005); ancient aeolian strata have been definitively identified in rover images (Banham et al., 2018; Edgar et al., 2012; Grotzinger et al., 2005) and inferred from orbiter data (Anderson et al., 2018; Bourke & Viles, 2016; Brothers et al., 2018; Day & Catling, 2018; Day et al., 2019; Ewing et al., 2010; Milliken et al., 2014). Analysis of cross-stratified sandstones using images acquired by Mars rover cameras has provided detailed insight into aeolian dune morphologies at Meridiani Planum and Gale crater (Banham et al., 2018; Barnes et al., 2018; Edgar et al., 2012; Hayes et al., 2011; Metz et al., 2009).

In Gale crater, earlier studies of the Stimson formation used mapping of the geometry and organization of cross-stratified sandstone to reconstruct a set of simple dunes from preserved stratigraphy over a 0.2 km² area on the Emerson plateau (Figure 1) (Banham et al., 2018; Barnes et al., 2018). Our study focuses on outcrops of the Stimson formation that form the bulk stratigraphy exposed in the Murray buttes (Figure 1), a set of isolated buttes and mesas located farther southwest into Gale crater than Emerson plateau, on the lower northwest flank of Aeolis Mons (informally Mount Sharp). Stimson formation strata exposed at the Murray buttes preserve the thickest, most laterally exposed, three-dimensional (3D) outcrops of aeolian strata encountered by the Mars Science Laboratory (MSL) as of the time of writing (cf. Banham et al., 2018; Banham et al., 2020a, 2002b; Banham, Gupta, Rubin, et al., 2020). The lateral and vertical continuity of this outcrop, combined with the high-spatial resolution images collected by the rover, Curiosity, have allowed for architectural reconstruction of the bedforms in similar detail as attained by studies of aeolian strata on Earth.

Here, we provide that reconstruction using data collected by the cameras onboard the Curiosity rover. The specific objectives in this study were to: (1) characterize the type of dunes, their size, and orientation as preserved in the rock record at the Murray buttes; (2) compare the recorded dune and sediment transport direction to other areas of the Stimson formation; and (3) comment on the dune field construction and evolution as expressed in the Murray buttes area. Our analysis reveals that the Stimson formation landscape consisted of a large dune field containing a hierarchy of aggrading compound dunes that migrated broadly to the north, downslope from Mount Sharp.





Figure 1. Study area. (a) HiRISE satellite mosaic showing the region of the traverse within Gale crater and the relationship to the major stratigraphic units mapped from orbit by Fraeman et al. (2016), on the north flank of Aeolis Mons. Inset map is an MRO context camera (CTX) mosaic showing the location of the traverse within the context of Gale crater. (b) Areas of Stimson formation outcrop encountered between Sols 964 and 1454 (yellow numerals). These areas represent discrete areas of outcrop encountered along the traverse. Base map is MSL Gale Merged Orthophoto Mosaic 25 cm/px was generated by Calef and Parker (2016). Image credit: NASA/JPL/University of Arizona. HiRISE, High Resolution Imaging Science Experiment.

2. Geological and Stratigraphic Setting

Gale is a 154 km diameter impact crater located on the Martian crustal dichotomy boundary, a topographic feature that divides the less cratered northern plains from the heavily cratered southern highlands (Carr et al., 1973). Gale is located ~5° south of the equator at 5.4°S, 137.8°E, and current understanding is that Gale has been at this latitude since it formed. The timing of the impact event that formed Gale is interpreted to coincide with the Noachian-Hesperian transition (Le Deit et al., 2013; Tanaka et al., 2014; Thomson et al., 2011; Werner, 2019) and is dated by crater counting to have occurred about 3.7 \pm 0.1 Ga (Le Deit et al., 2013; Thomson et al., 2011). Filling or partial filling of the crater with sedimentary strata is





Figure 2. Stratigraphic context of the Stimson formation. The stratigraphic column depicts key stratigraphic units encountered by the rover during the mission. The column shows units associated with the vertical elevation and does not account for total stratigraphic thickness.

inferred to have occurred during the Hesperian within 200-500 Myr after the crater formed (Grant et al., 2014; Grotzinger et al., 2015; Thomson et al., 2011). Mount Sharp preserves remnants of the stratified, lithified crater fill in a ~5 km high mountain (Anderson and Bell III, 2010; Thomson et al., 2011). Lower strata, explored using the Curiosity rover, include fluvial, deltaic, and lacustrine facies (Grotzinger et al., 2015). The ~4 km of rock above these, not yet explored via the rover, include a stratal package of sulphate-bearing rock (Milliken et al., 2010) which contains meter-scale cross-bedded sediments (Milliken et al., 2014), a light-toned, yardang-forming lens that also has meter-scale cross-bedded strata (Dromart et al., 2021), and a package above that which also has meter-scale cross-bedded strata (Anderson et al., 2018). All of the cross-stratified strata have been interpreted as aeolian sandstones. The topmost stratal package, exposed at the summit of Aeolis Mons, is a boulder-producing (i.e., lithified) package of strata that is not cross-stratified and has been interpreted as "duststones" (Grotzinger & Milliken, 2012; Lewis & Aharonson, 2014). Three very important observations pertain to the strata above those explored using the rover: (1) the sediments are lithified, all the way to the summit, implying some depth of burial and contact with diagenetic fluids, (2) meter-scale fracture and boxwork patterns in the sulphate-bearing unit also imply access to diagenetic fluids high up on Aeolis Mons (Siebach & Grotzinger, 2014), and (3) the cross-bedded stratal packages, interpreted as records of aeolian dunes, imply a progressive filling of Gale crater.

The stratigraphic section explored using Curiosity, and as established by the MSL Science Team, has been subdivided into three distinct lithostratigraphic groups: Bradbury, Mount Sharp, and Siccar Point (Figure 2). The Bradbury group, which comprised most of the first 100 m of succession traversed by the rover, is interpreted to consist of interfingered fluvial, deltaic, and lacustrine sedimentary rocks (Edgar et al., 2017; Grotzinger et al., 2014, 2015; Rice et al., 2017; Schieber et al., 2017; Stack et al., 2016; Williams et al., 2013). The Mount Sharp group encompasses the next >300 m of succession and is composed of the Murray formation: laminated lacustrine mudstones with minor intraformational fluvial sandstones (Edgar et al., 2020; Fedo et al., 2017; Grotzinger et al., 2015; Gwizd et al., 2020; Rivera-Hernández et al., 2020; Stack et al., 2019). At the time of writing, the Murray formation is the only unit in the Mount Sharp group encountered by Curiosity. Unconformably overlying exposures of Mount Sharp group strata is the Siccar Point group (Fraeman et al., 2016), a unit inferred to have accumulated on an aeolian deflation surface (Banham et al., 2018; Watkins et al., 2016). The Stimson formation is currently the sole unit encountered in this group at this stage of the rover's traverse;

however, the strata forming the Greenheugh pediment located south of Glen Torridon (immediately south of the Vera Rubin ridge) also sits unconformably on top of the Mount Sharp group, and is tentatively correlated to the Stimson formation (Banham et al., 2020a; Fraeman et al., 2016; Kronyak et al., 2019) (Figure 1). Siccar Point group rocks, whether Stimson formation or other unnamed formations, outcrop in patches all along the lower slopes of northern Aeolis Mons; Anderson and Bell (2010) called these occurrences the "mound skirting unit," or the "Washboard unit."

The Stimson formation is a decameters-thick unit of meter-scale cross-bedded mafic sandstone that unconformably overlies Murray formation mudstones (Banham et al., 2018; Bedford, Schwenzer, et al., 2020; Watkins et al., 2016; Yen et al., 2017). It outcrops between elevations (relative to the Martian datum: Smith et al. [2001]) of -4,460 m, where it was formally identified at a location named Mount Stimson, through to -4,290 m, where inferred Stimson outcrops are observed in orbiter images on the lower north flank of



Mount Sharp (Calef et al., 2013; Stack et al., 2017). It was encountered by the Curiosity rover between Sols 987 and 1454 and is a prominent cliff-forming unit across this segment of the traverse (a Sol is 1 Martian day, equivalent to 1.027 Earth days; mission Sols are consecutive from Sol 0, the local afternoon on which Curiosity landed in Gale crater). The Stimson outcrops studied via Curiosity are broken into four geographically distinct areas (Figure 1b): Emerson plateau, encountered Sols 987-1153 (Banham et al., 2018); Naukluft plateau, encountered Sols 1274–1357 (Banham et al., 2018; Bedford, Schwenzer, et al., 2020); and the focus of this study, the Murray buttes (Sols 1417-1455). The fourth area is the Greenheugh pediment, investigated between Sols 2658 and 2734 (Banham et al., 2020b; Bedford, Banham, et al., 2020; Bryk et al., 2020). The sand grains that compose the cross-bedded sandstone facies have a characteristic rounding and bimodal sorting (Banham et al., 2018) consistent with aeolian transport on Earth (Garzanti et al., 2015; Kuenen, 1960). Chemical variations measured at the sub-millimeter to decimeter scale by ChemCam (Bedford, Schwenzer, et al., 2020) indicate mechanical grain sorting might have been preserved in these sandstones, similar to the nearby, contemporary Bagnold dunes (Cousin et al., 2017). Cross-sets are composed of laminations of uniform thickness, interpreted to have been deposited by wind-ripples on the dune lee slopes (Hunter, 1977). Cross-sets are separated by sub-horizontal bounding surfaces, which are traced laterally for tens of meters; these are interpreted to be eroded by migration of troughs in the lee of migrating dunes (interdune surfaces, Kocurek, 1981b); first-order surfaces (Brookfield, 1977). Fine-grained interdune deposits are not observed at Emerson plateau, which suggests that the sands primarily accumulated by aerodynamic mechanisms in a dry aeolian dune field (sensu Kocurek and Havholm, 1994). Mapping of foreset dip-azimuths at Emerson plateau indicated a predominant trend toward the northeast, which was interpreted as the dominant dune-migration direction in the studied area of the ancient dune field (Banham et al., 2018).

In all three areas of Stimson formation outcrop, the rocks unconformably overlie the Murray formation. These individual areas are separated by lateral distances of no more than 250 m. The intervening gaps are interpreted to be areas from which Stimson formation rocks were eroded and removed, leaving the underlying Murray formation bedrock exposed (Watkins et al., 2016). All three areas of the Stimson formation are genetically related, due to their stratigraphic position, common outcrop expression, sedimentary structures, grain size, chemistry, and interpreted paleotransport directions (Banham et al., 2018; Bedford, Schwenzer, et al., 2020; Yen et al., 2017).

3. Data and Methods

3.1. Instrumentation

This study used data acquired by instruments aboard the MSL Curiosity rover and orbiting platforms to investigate the sedimentary textures and structures of Stimson formation rocks exposed in the rock faces of the Murray buttes in Gale crater.

The primary rover data came from photomosaics assembled from images acquired by the MSL Mast Cameras (Mastcams; Malin et al., 2017) and Navigation cameras (Navcams; Maki et al., 2012). The monochromatic (grayscale) Navcams provided 360° (azimuth) stereo pair coverage of the landscape that were used to (1) navigate the rover through the Murray buttes region (Figure 3), (2) fill gaps in coverage between Mastcam photomosaics, and (3) provide quantitative, 3D information (stereo meshes) used for measurement of rock unit thickness, lateral distances, and bedding orientations (dip). The fixed focal length color Mastcam consists of two instruments separated by an interocular distance of 24.64 cm and a toe-in angle of 2.5° for stereo (Bell et al., 2017; Malin et al., 2017). They are mounted on the rover's Remote Sensing Mast (Warner et al., 2016) ~1.9 m above the surface. Each Mastcam has a different optical design; the right camera (M100 or Mastcam right) has a focal length of 100 mm and a field of view (FOV) of ~6.9° × 5.1°; the left Mastcam (M34 or Mastcam left) has a fixed focal length of 34 mm and a FOV 20° × 15°. The instantaneous fields of view are 218 μ rad (M34) and 74 μ rad (M100); at a distance of 2 m, these provide spatial resolutions of 450 μ m/pixel (M34) and 150 μ m/pixel (M100). The Mastcams were primarily used to image the Murray butte outcrops to facilitate the identification of sedimentary structures, textures, depositional architectures, and stratigraphic relations.

The data from Mars-orbiting spacecraft came from the Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) and the Mars Global Surveyor (MGS) Mars





Figure 3. Overview orthomosaic of the Murray buttes study area and the path of the rover through the buttes. Each butte (outlined by a polygon) was predesignated a number to facilitate planning the traverse through the area. Yellow numerals indicate mission sols. Map source: Calef and Parker (2016).

Orbiter Laser Altimeter (MOLA; Smith et al., 2001). A photomosaic of HiRISE images of the MSL field site, assembled by Calef and Parker (2016), and a digital elevation model (DEM) produced from HiRISE stereo pairs tied to absolute Martian elevation derived from MOLA by Calef and Parker (2016) were used as base maps for photogeologic mapping and to determine the location of the rover and each Mastcam and Navcam mosaic.

3.2. Data Collection: Murray Buttes Imaging Campaign

The Murray buttes are located in a 0.25 km² area on the lower north flank of Aeolis Mons. They are a group of buttes and small mesas (see definitions of Duszyński et al. [2019]) of 5–16 m height separated by bare expanses of Murray formation exposures by distances ranging from a few meters of scree cover to hundreds of meters between nearest-neighbor slopes or cliff faces.

As shown in Figure 3, the Curiosity rover was driven southward through the Murray buttes between Sols 1410 (July 24, 2016) and 1468 (September 21, 2016). Throughout the traverse, the rover's wheels were on outcrops of the reddish, fine-grained (largely mudstone and very fine sandstone) rocks of the Hartmann's Valley and Karasburg members of the Murray formation (Gwizd et al., 2020; Rivera-Hernández et al., 2020). There were no opportunities for contact science of the in situ strata at the Murray buttes: slopes, talus, or strategically planned science commitments prevented the deployment of Curiosity's robotic arm (Robinson et al., 2013) to permit the use of the Mars Hand Lens Imager (MAHLI; Edgett et al., 2012) for macrophotography of intact Stimson formation rocks outcropping on the buttes or boulders, cobbles, or pebbles



derived from the Stimson formation shed from the buttes. This investigation also examined an 11 m thick outcrop of the Stimson formation encountered during Sols 1376 to 1384 named Baynes Mountain (Figure 1).

3.3. Nomenclature

The 12 Murray (M) buttes were assigned numbers (M1–M12) that progressed from north to south (Figure 3). In addition to the informal naming of the Murray buttes, M1 through M12, most other names of targets, landforms, and geologic units investigated via Curiosity are, although vital for communication, informal. The International Astronomical Union (IAU) determines formal names of features on Mars. In this contribution, Earth, Mars, Meridiani Planum, Gale, Aeolis Mons, Aeolis Palus, and Gediz Vallis are the only IAU designated features. All other names were assigned by the MSL team during surface operations using a scheme described by Vasavada et al. (2014). Internationally, Mars has no recognized formal stratigraphic code and, per tradition in the Earth and Mars geosciences (e.g., Grotzinger et al., 2005), all geologic unit names are informal and the terms facies, outcrop, member, formation, and group begin with lowercase letters.

3.4. Terminology for Cross-Stratification

In this contribution, a "cross-set" or a "set of cross-strata" is defined as a group of cross-strata or a package of cross-laminations that were deposited by the same migrating bedform (sensu McKee & Weir, 1953). Each cross-set consists of a package of cross-strata, bounded by an upper and a lower bounding surface. Here, the sub-horizontal bounding surface defining the cross-sets are described as set bounding surfaces. These surfaces are also described as first-order surfaces (Brookfield, 1977), interdune surfaces (Kocurek, 1981b), or dune bounding surfaces (Banham et al., 2018). Where related to compound cross-sets observed in the Murray buttes area, these are given the descriptive term of compound-set bounding-surfaces. The compound cross-set can also be described as a coset.

Cross-bedding can be simple—not containing internal erosion surfaces—or it can be compound—containing internal erosion surfaces (sensu, Rubin & Hunter, 1983). Erosional boundaries within a compound set—here termed subset bounding surfaces (sensu, Hunter & Rubin, 1983)—can be formed by two distinct mechanisms. The first, caused by changes in dune size or dune migration direction, generate reactivation surfaces (termed third-order surfaces by Brookfield [1977] and Schenk et al. [1993]). The second, caused by migration of scour troughs in the lee of superimposed bedforms, generates superposition surfaces (termed second-order surfaces by Brookfield [1977] and Kocurek [1991]). Although these two types of subset bounding surfaces form by different mechanisms, they can appear somewhat similar. They can generally be distinguished where 3D observations are available (Rubin, 1987a; Rubin & Hunter, 1983).

3.5. Data Analysis

3.5.1. General

Analysis of the Mastcam and Navcam images—as well as the HiRISE image products of Calef and Parker (2016)—used in this study were performed via a combination of standard remote photogeology methods (e.g., De Hon et al., 2001; Moore, 1971; Nesbit et al., 2020; Ray, 1960). The overall methods followed those of Banham et al. (2018).

Before analysis, the Mastcam and Navcam images of the Murray buttes were radiometrically calibrated, white balanced, and geometrically corrected for lens distortion (e.g., Bell et al., 2017). Then the images were mosaicked with adjustments to preserve geometric relations. Navcam stereo pair mosaics were used to triangulate distances and generate a 3D mesh (see Alexander et al., 2006). This mesh was also used for measuring geological features, such as the thickness of stratal packages, laminations, lateral extents, and camera working distances of the observations. The spatial resolution offered by the mesh is typically decimeter-scale at decameter distances, and centimetre-scale at meter distances. In this study, observations were typically made at decameter distances. Mosaics were interpreted using vector graphic software (Section 3.5.3) to highlight the various depositional packages, bounding surfaces, and their architectural relations.



3.5.2. Cross-Bed Dip Analysis

Quantitative analysis of cross-bed orientations used the methods described by Banham et al. (2018). Foreset dip-azimuths and the dip-azimuths of subset bounding surfaces were recorded in a database along with their Cartesian coordinates, allowing projection of the measurements onto the HiRISE orthomosaic of Calef and Parker (2016). Statistics related to foreset dip-azimuth and subset surface dip-azimuth measurements—such as vector mean and vector magnitude—were calculated using methods described by Lindholm (1987) to determine the mean bearing of the bedform migration direction. Observation distance from the rover typically ranged 20–70 m, with the closest observations made at ~15 m from the buttes, and farthest observations at ~250 m distance. Due to the increased distances of observation compared to the previous study at Emerson plateau (Banham et al., 2018), and data volume acquisition and downlink constraints at the time of the traverse through the buttes (Section 3.2), stereo pair Mastcam data were collected across just a few buttes, which limits the use of digital outcrop models for analysis of the dip-azimuths.

3.5.3. Digital Outcrop Model Analytical Tool and Methods

Textured 3D outcrop models (DOMs) generated from stereo images in the Planetary Robotics Vision Processing tool (PRoViP, Paar et al., 2012), using processed Mastcam frames (Paar et al., 2012) were interpreted using the Planetary Robotics 3D viewer (PRo3D) (Paar & Consortium, 2016; Traxler et al., 2018). This software was used to measure geometries and dimensions of geological features observed in the outcrops, such as cross-set thicknesses and dip-azimuth and dips of depositional surfaces. A comprehensive description of these methods was provided by Barnes et al. (2018).

4. Results

4.1. Regional Stratigraphic Relations at the Murray Buttes

The Murray buttes are discontinuous Stimson formation outcrops that cover roughly 0.12 km^2 of an area of 0.25 km^2 , between elevations -4,430 and -4,370 m. The buttes rest on the base Siccar Point group unconformity, are between 8 and 16 m tall, and are capped by an erosion-resistant, sharp-edged sandstone layer. The lower portions of the buttes are typically slope-forming and are partially occluded by debris derived from the breakdown of the caprock and by wind-blown sand and dust. The basal unconformity occurs at the break-in-slope at or near the base of each buttes. Where debris or regolith cover is limited, sedimentary structures and architectural elements typical of the Stimson formation are discerned in sections of the lower slopes of the buttes.

The topographic relation between the basal unconformity and overlying Stimson formation at the Murray buttes is illustrated in Figure 4, a plot of the elevation of the unconformity and height of butte tops projected along a north to south profile. This plot shows that the elevation of the unconformity rises toward the south and parallels the modern slope—the rover traverse elevations in Figure 4—as also noted by Watkins et al. (2016). Over the length of the profile, the elevation of the unconformity rises from -4,430 m at Baynes Mountain to -4,370 m at butte M12 in the south. The spread of unconformity spot heights along this profile indicates that the unconformity is undulating at the meter-scale, and that it is not a flat, smooth plane (Watkins et al., 2016). The total elevation change from Baynes Mountain to butte M12 is ~60 m over a horizontal distance of 1 km. The elevation of the Murray butte tops mirrors the rise in the elevation of the unconformity with buttes maintaining a similar height as traced southwards. It is unclear if the Stimson formation rocks record a single layer tracking the unconformity or if they record sediment packages that systematically pinch out southwards against the unconformity. Locally, however, we do observe sedimentary packages pinching out against the unconformity (e.g., along the north-south face of butte M11).

4.2. Sedimentary Facies

4.2.1. Description

A comprehensive description of lithofacies observed in other areas of the Stimson formation was given by Banham et al. (2018), and only a summary review of facies encountered within the Murray buttes is given here. Within the Murray buttes area, the dominant Stimson formation facies consists of cross-bedded





Figure 4. Elevation of the base Stimson unconformity (also known as the base Siccar Point unconformity), from the south margin of the Naukluft plateau, to the south margin of the Murray buttes. The orange points denote the elevation of the rover along the traverse, with the blue points indicating the elevation of the unconformity at locations around the base of the buttes, as observed from the rover using the Mastcam instrument. The green points are spot heights for the butte tops, taken from HiRISE-derived DEM models. Triangles indicate the end-of-sol rover locations. DEM, digital elevation model; HiRISE, High Resolution Imaging Science Experiment.

sandstones: at the Emerson plateau, Banham et al. (2018) named this facies 1—meter-scale planar and trough cross-bedding) (Figure 5). The cross-sets are composed of millimeter-thick, uniform-thickness laminations—pinstripe laminations—that are laterally persistent for tens of centimeters to a couple of meters (Figure 5). Cross-laminations are curvilinear and asymptotically downlap onto a lower erosional bounding surface; in addition, they are truncated by an upper bounding surface. The hierarchical relations between these bounding surfaces are described below in the description of butte M1b. Cross-sets throughout the study area typically range between 0.3 and 1.0 m thick.

No direct grain size measurements were possible at the Murray buttes. The closest approach between the rover and the Stimson outcrops was ~ 15 m at Butte M12 (Figure 3). At a 15-m distance, the M100 cameras have a spatial resolution of ~ 1.1 mm/pixel, which allows for delineation of visually contrasting grains down to $\sim 2-3$ mm in size. If grain size in the Murray buttes is similar to that of the Emerson plateau area, then grains would not be resolvable in any of the M100 mosaics.

4.2.2. Interpretation

The presence of abundant large-scale cross-bedding within the Stimson formation at the Murray buttes, which is morphologically similar to those cross-sets observed at Emerson plateau area by Banham et al. (2018) supports the interpretation of an aeolian origin for the Stimson formation rocks exposed at the Murray buttes. The cross-bed sets are interpreted to have formed by accretion along the lee slope of migrating dunes, with the asymptotically curved cross-laminations reflecting the curved toe of the dune at the base of the lee slope. The lower bounding surface of a cross-set is a time-transgressive surface formed by scouring as the trough in the lee of an advancing dune migrates downwind. The bounding surface defining the top of a cross-set is formed in a similar manner but through scouring by migration of the trough in the lee of an upwind dune.

The millimeter-thick, uniform-thickness laminae—pinstripe laminations—are interpreted to have formed by migration of wind ripples across the lower section of dune lee-slopes (sensu, Clemmensen & Abrahamsen, 1983; Fryberger & Schenk, 1988; Hunter, 1977). These are identical to those observed elsewhere in the Stimson formation (Banham et al., 2018).





Figure 5. Representative example of Stimson formation facies in the Murray buttes. These facies correspond to Facies 1: Meter-scale planar and trough-crossbedded, described by Banham et al. (2018). The annotated diagram depicts the key geometric relations of depositional packages to bounding surfaces. Image recorded at Butte M12 (M100 Mastcam mosaic, acquired on Sol 1455, mcam07200, at end-of-Sol 1454 rover position).

Typically, aeolian strata on Earth are composed of three kinds of primary stratification: grainfall, grainflow (avalanche), and wind-ripple strata (Fryberger, 1993; Hunter, 1977; Kocurek, 1996). Although these varieties can often be distinguished texturally at distances closer than 1–2 m, at longer distances, it can be difficult to identify differences in grain size and difficult to see laminae thinner than a few millimeters. As with observations at Emerson plateau, no evidence for grainflow strata were discerned, and the increased distance from which the outcrop was observed at the Murray buttes would further decrease the chance of identifying grainflow strata. Because the process of deposition is interpreted to be identical between the two areas, the sedimentary texture and corresponding average grain size are likely to be similar; MAHLI observations at Emerson plateau showed the sand grains are typical ~0.4 mm in size (Banham et al., 2018).

4.3. Reconstructing Dune Morphology from Sedimentary Architectures

Here, we reconstruct the morphology of the sedimentary system recorded by the Stimson formation at the Murray buttes based on observations of the set architecture of cross-strata and the geometric relations of the bounding surfaces separating the cross-strata. The hierarchical relations between depositional packages and erosional surfaces observed here have been recognized based on studies of aeolian stratigraphy



Figure 6. Butte M1b, to illustrate and define the depositional packages and their bounding surfaces. (a) Overview image of butte M1b, showing the relation of the Stimson formation outcrop to the base Stimson unconformity, and the general outcrop expression. The outcrop face is broadly oriented between azimuths 090° and 270°. (b) Uninterpreted view of the area-of-interest highlighted in image (a). (c) Interpretation of depositional packages and bounding surfaces. (1) denotes the sub-horizontal compound-set bounding-surface (interdune surface), and (2) denotes the inclined subset bounding surfaces (superposition surface). White lines trace cross-laminations. (d) Detail of an area in (c) showing relations between compound-set and subset bounding surfaces. (e) Idealized schematic representation of the depositional packages and bounding surfaces observed at Butte M1b.

and depositional environments on Earth (Ballico et al., 2017; Blakey, 1988; Blakey et al., 1988; Chan & Kocurek, 1988; Clemmensen & Abrahamsen, 1983; Clemmensen & Blakey, 1989; Fryberger & Schenk, 1988; Kocurek, 1981a, b, 1988; Kocurek & Havholm, 1994; Loope & Simpson, 1992; Marzolf, 1988; Mountney, 2006; Mountney & Jagger, 2004; Porter, 1987; Reiche, 1938; Rubin & Hunter, 1983; Scherer, 2000). This enabled the reconstruction of the morphology of dune assemblages that existed in this region of Gale crater at the time the Stimson formation sands were deposited.

4.3.1. Butte M1b: Defining Depositional Packages and Their Bounding Surfaces

Butte M1b illustrates our methods and outlines the primary stratigraphic geometries observed.

4.3.1.1. Description

The south-facing side of Butte M1b (Figure 6a) has a height of 8 m and a length of 45 m. The sub-Stimson unconformity is observed at the base of the butte and exhibits sub-meter amplitude undulations. Beds in the

lowermost part of the Stimson onlap the unconformity, indicating that it had local paleo-relief. While the lowermost cross-bed sets are largely obscured by talus and wind-blown sand, the upper part of the outcrop forms a well-exposed cliff approximately 4 m in height.

A detailed view of the cliff section (Figure 6b) is interpreted in Figure 6c. Tracing cross-laminations and their intersecting bounding surfaces reveal the sedimentary architecture. Cross-laminations show a characteristic curvature with a high angle of dip in the upper section of a cross-set that progressively decreases in dip toward the base of the set where they downlap onto a lower erosional surface, commonly converging asymptotically with it (labeled "a" in Figure 6c). Each cross-set is truncated by an upper erosional bounding surface defining the base of the overlying set (labeled "b" in Figure 6c). Individual cross-bed sets are separated from one another by these erosional bounding surfaces, which are inclined at a much lower angle than the average dip of the cross-sets. We identify different types of bounding surfaces based on their geometry and relations to other surfaces per (Brookfield, 1977; Kocurek, 1981b).

The first bounding surfaces to be mapped were those that could be traced for distances of tens of meters, commonly across the width of an outcrop. These decimeter-length surfaces (annotated orange in Figure 6) are horizontal or sub-horizontal in inclination and are expressed as a single well-defined and easily traced surface, or by a set of coalesced intersecting bounding surfaces at a common stratigraphic horizon. These surfaces define coset boundaries (sensu, McKee & Weir, 1953); cosets are groups of associated cross-bed sets. For descriptive (non-genetic) purposes, we refer to these sub-horizontal surfaces as compound-set bounding-surfaces.

Within cosets, cross-bed sets are also separated by laterally discontinuous and typically inclined bounding surfaces (surface 2: annotated yellow in Figure 6c). These can only be traced for short distances, typically decimeters, but occasionally up to 1–2 m, before they are truncated by another bounding surface. These surfaces are characterized by cross-laminations downlapping onto them ("c" in Figure 6d). They can be truncated by overlying surfaces ("d" in Figure 6d), but rarely cross-cut the underlying sub-horizontal compound-set bounding-surfaces. Instead, they converge asymptotically with these compound-set bounding surfaces ("e" in Figure 6d). Where inclined bounding surfaces scour into the larger-scale horizontal (orange annotated in Figure 6) bounding surfaces, they do so at a low angle. This results in the horizontal (compound-set) bounding surface having an irregular appearance. The inclined bounding surfaces (annotated yellow in Figure 6) fit the criteria for subset bounding surfaces (sensu, Rubin & Hunter, 1983). Cross-bed sets are truncated at their top by either a subset or compound-set bounding-surface. Thus, in Butte M1b, cross-bed sets are separated by a hierarchy of bounding surfaces that exhibit differing geometries.

4.3.1.2. Interpretation

The arrangement of bounding surfaces is summarized in a schematic diagram displayed in Figure 6e. The compound-set bounding-surfaces ("1" in Figures 6c–6e) are interpreted following Brookfield (1977) and Kocurek (1981) as erosional surfaces formed by forward migration of a trough or scour pit at the base of the lee slope of an advancing large dune—a "primary dune" or "draa." Such surfaces have been referred to as interdune surfaces (Mountney & Thompson, 2002) or as dune migration surfaces within the Stimson formation (Banham et al., 2018). A coset of cross-strata that contains subsets of cross-strata is referred to as a compound set. Compound sets can form either by superimposed bedforms migrating on the lee side of the primary bedform, by reversing flows, or by any form of scouring that would rework the lee side of a dune. In Stimson outcrops, stratification varies in dip-azimuth from one set to another in the coset, suggesting deposition by superimposed bedforms rather than by repeated reversals of the primary dune (Hunter & Rubin, 1983; Rubin & Hunter, 1983; Rubin, 1987). Such inclined subset bounding surfaces ("2" in Figures 6c–6e) have been described as "bounding surfaces scoured by superimposed bedforms" (Rubin & Hunter, 1983) or superposition surfaces (Kocurek, 1991); they were eroded by migration of troughs or scours in the lee of smaller scale dune groups superimposed on the primary dune (Brookfield, 1977).

An alternate interpretation could be that the subset bounding surfaces record reactivation surfaces ("3" in Figure 6e), preserved in a simple cross-set, that were generated by changes in dune size and migration direction (sensu, Hunter & Rubin, 1983). This interpretation may be true for some cross-sets within the Murray buttes area but no simple sets were clearly identified within the Murray buttes. An interpretation of oblique





Figure 7. Schematic representation of the depositional packages and their relation to the lower bounding surface. Simple cross-bedding (sensu Banham et al., 2018) is ideally characterized by cross-laminations downlapping onto the lower bounding surfaces (1). The dark gray shading highlights a depositional package on the lee-slope of the dune. Compound cross-bedding is ideally characterized by cross-sets downlapping onto a subset bounding surface (2). The gray area (a cross-set bounded by two inclined subset bounding surfaces) denotes deposition on the lee slope of a primary dune (or draa).

compound dunes is favored based on the dip-azimuth relations of cross-laminations and superposition surfaces observed across the study area. The discussion of Butte M4 describes these relations below.

Figure 7 summarizes the contrasting geometry of depositional packages for both simple and compound cross-bedding. Cross-laminations compose the smallest depositional package that typically accumulates on the lee slope of a dune and are the primary constituent of cross-sets. For simple cross-bedding, cross-laminations record the main depositional package that accumulates on the lee slope of a dune (dark gray area in Figure 7a). For compound cross-bedding, cross-laminations still form the cross-sets, but the cross-sets now represent larger depositional packages on the lee slopes of larger primary bedforms (gray packages, deposition on draa lee in Figure 7)

In summary, for the compound cross-sets observed in Figure 6, and summarized in Figure 7b, individual cross-laminations (white traces in Figure 6) record sediment accumulation on the lee slope of a superimposed bedform; a cross-set bounded by subset bounding surfaces (interpreted as superposition surfaces) records the deposit of a superimposed dune on the lee slope of a primary dune; a coset bounded by a compound-set bounding-surface (interpreted as interdune surfaces) indicates the passage of a primary dune—a large dune or draa—with smaller bedforms superimposed on it (Lancaster, 1988b; Wilson, 1973). The style of cross-stratification observed at the Murray buttes is termed "compound cross-stratification"—this forms where smaller, superimposed bedforms migrate faster across the surfaces of larger, slower moving draascale bedforms (Lancaster, 1988a), generating small-scale cross-bedding on the lee-slope of the larger bedform (Allen, 1968; Brookfield, 1977; Rubin & Hunter, 1983). The geometry of preserved cross-stratification is dependent on morphology and motion of superimposed dunes on the lee slope of larger primary dune. The shape of the superimposed dunes and whether they migrated down the lee slope of the primary dune obliquely or perpendicular to it creates highly variable stratal geometries (Rubin, 1987a; Rubin & Hunter, 1983); this point is explored in subsequent sections.

4.4. Variability of Compound Cross-Stratification at the Murray Buttes

Now that the hierarchy of bounding surfaces, their geometric relations, and our annotation scheme (Figures 6 and 7) have been established, this section describes the range of variability in sedimentary architecture observed in Stimson formation outcrops at the Murray buttes.





Figure 8. Baynes Mountain at Naukluft plateau (see Figure 1) exhibits similar stratigraphic architecture as observed in Stimson outcrops in the Murray buttes. (a) Uninterpreted overview of Baynes Mountain showing lateral extent of the outcrop. The outcrop is 11 m tall and approximately 65 m long. The outcrop face is oriented between azimuths \sim 150° and 350°. (b) Interpreted close-up mosaic of the stratigraphic architecture. Orange traces indicate compound-set bounding-surfaces, yellow traces mark inclined subset bounding surfaces. Cross-laminations in this mosaic are observed to dip toward the north and northeast. Mastcam mosaic mcam06791, acquired on Sol 1384 from end-of-Sol 1383 rover location, at a distance of \sim 50 m.

4.4.1. Baynes Mountain—Lateral Extent of Compound-Set Bounding-Surfaces

4.4.1.1. Description

Baynes Mountain is the most southwesterly outcrop of the Naukluft plateau observed on the traverse (Figure 1b) and is included here to link the stratigraphic architecture of the Stimson formation rocks observed in the Naukluft plateau with that of the Murray buttes. Baynes Mountain forms an 11-m tall outcrop of Stimson formation sandstone that unconformably overlies the Murray formation (Figures 1b and 8).

On the east face of Baynes Mountain, cross-bedded sandstones are subdivided by four sub-horizontal bounding surfaces (labeled BM_ID1-ID4 in Figure 8) that extend laterally across the outcrop in excess of 30 m (Figure 8). They appear to maintain an approximately constant elevation across the outcrop, although they do apparently undulate by a few decimeters over distances of 10 m. These surfaces bound three cosets that have thicknesses between 1 and 2.7 m. Within the cosets, individual cross-sets occur between inclined bounding surfaces (yellow traces in Figure 8) that are not as laterally extensive as the compound-set bound-ing-surfaces, which span the width of an outcrop. Individual cross-sets range from ~0.3 to 1 m in thickness. Cross-laminations throughout the outcrop have an apparent dip that is predominantly toward the north-east; however, there are several examples where the cross-sets are viewed along a cross-bed trough-axis.

4.4.1.2. Interpretation

The observed horizontal surfaces are interpreted as time-transgressive surfaces generated by migration of scours in the lee of advancing primary dunes. These surfaces appear horizontal because the typical angle of climb of primary dunes is of the order of $0.3^{\circ}-2^{\circ}$ (a gradient of 1/50 or 1/25) for transverse dunes (Mountney, 2006; Rubin & Hunter, 1982), which would be too slight to observe without precise measurement. To compound the complexity of measurement of the true angle of climb, the regional dip of the underlying unconformity is approximately 2° toward the north (Watkins et al., 2016). The undulations of the interdune surfaces at a local scale could have arisen by two mechanisms: by changes in the geometry of the scour



trough as it migrated through this point in 3D space (Rubin & Carter, 2006), or as a result of fluctuations in sediment supply, causing the primary dune to change its angle of climb (Kocurek & Havholm, 1994). Other causes can be the interaction of superimposed dune scour troughs with the scour troughs of the primary dune, or changes of dune height as a result of changing wind speed and direction (Rubin, 1987b; Rubin & Hunter, 1983).

4.4.2. Butte M4: Relations Between Cross-Laminations and the Orientation of Compound-Set and Subset Bounding Surfaces

4.4.2.1. Description

Butte M4 (Figure 9) is suitable for the detailed examination of the relationship between foreset dip-azimuths of cross-beds and bounding surface dip-azimuths. Two sides of the butte were imaged: the north-facing side was viewed from distances of approximately 70 and 30 m, showing the broad-scale architecture and fine-scale facies (Figure 9b); and the west-facing side was observed at a distance of 30 m. These different viewpoints provide data on the three-dimensionality of foresets and bounding surfaces (Figure 9a).

Butte M4 has a maximum height of 16 m. The unconformity beneath the Stimson formation is visible at the base of the butte on its north and west sides, and it undulates by an amplitude of a few meters over the width of the outcrop. Stimson strata are only well exposed in the upper parts of the butte. To characterize the relation between different bounding surfaces and depositional units, we first describe the west-facing side of the outcrop (Figure 9a).

Compound cross-sets occur on the west face (Figure 9a); these are defined by their constituent bounding surfaces. Four, sub-horizontal compound-set bounding-surfaces (M4-ID1 to M4-ID4; annotated orange, in Figure 9a) are observed. All four surfaces extend from the left (north end of the west-facing side), and across the outcrop, for approximately 18 m to the right side (south end), where they are obscured by regolith. Cosets 2 and 3 are relatively uniform in thickness across the outcrop, with thicknesses ranging between ~2 and 3 m. Within these cosets, we identified a series of subset bounding surfaces. These bounding surfaces (traced in yellow) are inclined relative to the compound-set bounding-surfaces and have an apparent dip toward the left side of the mosaic (north). At their base, these surfaces downlap onto the lower compound-set bounding-surface, whereas the upper termination is truncated by an overlying compound-set bounding-surface. Subset bounding surfaces bound sets of cross-laminations. These cross-laminations (white traces) dip asymptotically onto the subset bounding surface beneath them and are truncated by the overlying subset bounding surface. Here, the cross-laminations have an apparent dip direction toward the north, similar to the subset bounding surfaces. However, they typically dip at a steeper angle relative to the subset bounding surfaces. Within the sets, the cross-laminations are concordant and are uniform in width along their length.

The compound-set bounding-surfaces identified on the west-facing side (M4_ID2-4) were also traced onto the north face of Butte M4 (Figures 9b and 9c), where they exhibit the same sub-horizontal geometry. This indicates that they are sub-horizontal in three dimensions. Again, these compound-set bounding-surfaces were traced across the width of the north face of the outcrop, where they bound the same cosets. The cosets thicken slightly toward the left of the outcrop (toward the east), suggesting that the compound-set bound-ing-surfaces might not be truly horizontal.

When viewed at a close distance on the north face (Figure 9b), individual cross-laminations are sub-parallel and uniform in thickness. Cross-laminations within the sets in the north face show an apparent dip toward the east (left in Figure 9b), where they down-lap asymptotically onto an underlying bounding surface and are truncated at a high angle by an upper bounding surface. These cross-sets have thicknesses of 0.3–0.7 m. When viewed from a distance (Figure 9c), the subset bounding surfaces that encompass these cross-sets are slightly inclined to the west (toward the right of the image in Figure 9c), and are inclined relative to the compound-set bounding-surfaces. The key difference from the west-facing side is that the cross-laminations dip in the opposite direction to the subset bounding surfaces. This is best illustrated in coset 2 (Figure 9c), in which the cross-laminations are seen to apparently dip steeply to the east, whereas the subset bounding surfaces dip shallowly to the west of the outcrop.





Figure 9. Butte M4, the butte that best illustrates the geometric relation between compound-set and subset bounding surfaces, and cross-laminations. (a) West-facing side of Butte M4, oriented between azimuths 156° and 336°. Cross-sets and subset bounding surfaces apparently dip toward the left, that is, toward the north. Compound-set bounding-surfaces, which bound cosets (orange) are largely horizontal. Mastcam mosaic mcam07074, obtained on Sol 1432, from end-of-Sol 1431, from a distance of 30 m. (b) Interpretation of north-facing side of Butte M4 which is oriented between azimuths 070° and 250°, from a distance of 30 m. Cross-laminations are observed with apparent dips toward the left of the outcrop—apparently toward the east. Second-order surfaces apparently dip shallowly toward the right of the outcrop—toward the west. Mastcam mcam07068 taken on Sol 1429, from end-of-Sol 1428 rover location. (c) Interpretation of north-facing side of Butte M4, from an increased distance of 70 m, which better demonstrates the dipping nature of the subset surfaces. Mastcam mosaic mcam06999 acquired on Sol 1418, from end-of-Sol 1417 rover location.

4.4.2.2. Interpretation

The geometry of cross-stratified units and the bounding surfaces observed in the two faces of Butte M4 permits reconstruction of the 3D geometry of paleosurfaces and cross-bed units. Compound-set bound-ing-surfaces (annotated orange in Figure 9c) are sub-horizontal in both faces, which indicates that they are

sub-horizontal in three-dimensions. The subset bounding surfaces (annotated yellow in Figure 9c) dip at a shallow angle to the west in the north face and dip steeply to the north in the west face. Combining the dip-azimuths of these subset bounding surfaces observed from the two different sides of the butte gives a true dip-azimuth of the subset bounding surfaces. The dip of the subset bounding surface broadly approximates the migration direction (subset bounding surfaces do not form parallel to the original lee slope) of the primary dune, toward the north-northwest, with superimposed lee-face bedforms having apparently migrated obliquely along slope toward the northeast. For cross-laminations, the apparent dip is toward the north. This gives an approximate true cross-lamination dip-azimuth toward the northeast.

The compound-set bounding-surfaces were formed by the migration of troughs in the lee of advancing primary dunes. The subset surfaces were formed by scours advancing in the lee of superimposed dunes as they migrated obliquely across the lee-slope of the primary dune (cf. Brookfield, 1977). These surfaces reflect the dip-azimuth of the lee slope of the primary dune and its direction of migration. The cross-lamination dip-azimuths in this outcrop are typically oriented toward the northeast, whereas the superposition surface dip-azimuths are typically oriented toward the north and northwest. This indicates that the smaller superimposed bedforms were migrating obliquely across or perpendicular to the primary dunes (cf. Rubin, 1987a). To get a better understanding of this outcrop, we analyze the 3D relations of these surfaces in Section 4.5.

4.4.3. Butte M7b: Sinuosity and Migration Direction of Superimposed Bedforms

4.4.3.1. Description

Cross-laminated sets and bounding surfaces are exposed in the main cliff on the western tip of Butte M7, both on the northwest-facing side (Figure 10a) and the west-facing side (Figure 10b). On the northwest face (Figure 10a), cross-laminations have an apparent dip toward the east (to the left of the image). Bounding surfaces are close to horizontal and do not exhibit a preferential apparent dip direction. Because of the apparent horizontal dips of these bounding surfaces, it is difficult to distinguish compound-set bounding-surfaces from subset bounding surfaces without tracing them from the adjacent west-facing outcrop.

The west-facing side of the butte (Figure 10b) exposes \sim 6.5 m of vertical outcrop, in which cross-laminations tions and compound-set and subset bounding surfaces are readily observed. Here, the cross-laminations have apparent dips toward the north and are arranged in sets 0.25- to 0.5-m thick (see coset 1, bounded by ID1 and ID2, in Figure 10b). Subset bounding surfaces dip toward the north at a shallower angle than the cross-laminations, with cross-laminations downlapping onto a lower bounding surface, and truncated at a high angle by an upper bounding surface. Compound-set bounding-surfaces can be tentatively distinguished from subset bounding surfaces by their less steep dips and greater lateral extent, whereby they can be traced across the width of the outcrop—approximately 5–8 m. The best-exposed cosets, bounded by the compound-set bounding-surfaces are approximately 3.5-m thick (ID2–ID3 in Figure 10b) and ~2.5-m thick (ID3–ID4).

4.4.3.2. Interpretation

The relatively planar shape of the subset bounding surfaces on the north side of Butte M7b suggests that the superimposed bedforms that scoured them were relatively straight-crested, which resulted in more planar scour surfaces. The horizontal orientation of the superposition surfaces suggests that the plane of the outcrop is oriented close to the strike of superposition surfaces. When the outcrop is viewed from the west-facing side, the superposition surfaces show apparent dips toward the north. This indicates that the primary dune lee-slopes have true dip-directions toward the north or north-northwest.

4.4.4. Butte M9c: Relations Between Dips of Cross-Laminations and Subset Bounding Surfaces

4.4.4.1. Description

Butte M9c is ~ 10 m tall and has a good exposure of the Stimson formation at the northern end of the outcrop (Figures 11a). Butte M9c was observed from a distance of 140 m looking toward azimuth 054°. Here, cross-set laminations show a unique relation to their associated bounding surfaces, which provides insight into dune kinematics at this location. Two distinct outcrop-scale (approximately 20 m in length) sub-horizontal

Figure 10. Butte M7b, shows the migration direction of the superimposed bedforms. (a) Interpreted mosaic of the northwest-facing side of Butte M7b, oriented between azimuths 075° and 255°. Here, the subset bounding surfaces are broadly sub-horizontal, while cross-laminations are observed to dip toward the left of the image—apparently toward the northeast. Mastcam mcam07087, taken on Sol 1434, from end-of-Sol 1433 rover location. (b) Interpreted mosaic of the west-facing side of Butte M7b, oriented between azimuths 000° and 180°. Here both the subset surfaces, and the cross-laminations dip toward the left of the outcrop—apparently toward the north. Mastcam mosaic mcam07099 acquired on Sol 1436, from end-of-Sol 1435 rover position.

compound-set bounding-surfaces (M9c-ID1 and ID2 in Figures 11a) subdivide the succession. Between these two surfaces is a ~4 m thick coset. The cross-sets that make up this coset are bounded by subset bounding surfaces that have an apparent dip toward the north (left in Figures 11a). Within these cross-sets, there are examples of horizontal or near-horizontal laminations. The cross-laminations within the basal cross-set downlap onto compound-set bounding-surface ID1 ("a" in Figures 11a), whereas cross-laminations within the overlying cross-sets terminate onto subset bounding surfaces ("b" in Figures 11a). These cross-laminations are themselves truncated by subset surfaces. At the top of the coset, cross-laminations and inclined subset surfaces are sharply truncated by the overlying compound-set bounding-surface ID2 ("c" in Figures 11a). This relation between cross-bed foresets and subset bounding surfaces suggests that the cross-beds accreted obliquely up the subset bounding surfaces toward the northeast (from left to right in Figure 11a).

Figure 11. Butte M9c, showing key relation between cross-laminations and subset bounding surfaces. (a) Interpreted mosaic of the north-end of Butte M9c, outcrop is oriented approximately north-south. Cross-laminations here are observed to be horizontal relative to the inclined subset bounding surfaces. Mastcam mosaic mcam07194, taken on Sol 1454, from end-of-Sol 1452 rover location. (b) Schematic representation of compound cross-strata created by superimposed dunes migrating perpendicular to the draa crest (left) and compound cross-strata generated by superimposed dunes migrating obliquely up the draa's lee slope (right), showing the geometric relation between cross-laminations and the viewing angle of the cross-section. The green cross-section through the compound dunes is what we interpret to be observed in (a).

4.4.4.2. Interpretation

The orientation of the subset bounding surfaces relative to the cross-lamination dip-azimuths provides insight into the direction that the superimposed bedforms migrated across draa-scale bedforms. If the cross-lamination dip-azimuth diverges from the dip-azimuth of the superposition surfaces, it indicates that the superimposed bedforms did not migrate directly down the lee slope of the primary dune. They must have migrated with an along crest component—either directly along slope or obliquely up or down the lee slope of the primary dune. Migration of superimposed dunes toward a preferred clockwise or counter-clockwise direction relative to the main dunes indicates that the main dunes were oriented obliquely to the overall transport direction (Rubin, 1987; Rubin and Hunter, 1983, 1985).

At Butte 9c, the divergent migration direction of the two orders of bedforms is readily observed. The cross-laminations within the central coset largely appear horizontal, or apparently dip toward their subset bounding surfaces. To generate this geometric arrangement, superimposed dunes would have needed to migrate obliquely up the primary dune lee slope (Figures 11b, right). If the superimposed dunes migrated perpendicular to the primary dune crest (across the lee slope), the cross-laminations seen in the outcrop would apparently dip toward the north (conceptualized in Figures 11b, left).

Figure 12. Butte M10 is where the thickest cosets in the Murray buttes area are observed. The outcrop face is oriented between azimuths 163° and 343°. Cosets of up to 3.5 m thick are observed, composed of cross-sets of 0.6 and 0.7 m thick. Mastcam mosaic mcam07110, obtained on Sol 1438, from end-of-Sol 1435 rover location.

Similar outcrop geometries have been observed on Earth and have been simulated using numerical models by Rubin (1987a). An example of similar cross-set geometries is observed at Johnson Canyon, Utah, within the Navajo Sandstone (Rubin & Carter, 2006, Figure 75), in which cross-laminations dip in the opposite direction to their associated subset bounding surfaces. Rubin and Carter (2006) reproduced the observed stratigraphic architecture by simulating a superimposed bedform that changed migration direction frequently, so as to migrate obliquely up the primary dune lee-slope, and then migrate obliquely down the primary dune lee-slope. The crest of the superimposed bedform was aligned at ~45° to the crest of the primary dune. This suggests that to generate similar stratigraphy, a multimodal wind regime is required, with wind driving superimposed dunes obliquely up the primary dune to generate these patterns (Courrech du Pont, 2015; Rubin & Hunter, 1987). These winds could have arisen from mechanisms external to the dune field, such as seasonal, regional wind-direction changes, or by daily changes in temperature which would generate katabatic winds, or from processes internal to the dune field, such as turbulence generated by upwind large dunes.

4.4.5. Butte M10: Architecture of the Largest Observed Compound Dune

4.4.5.1. Description

The largest cosets observed in the study area are at the southeastern margin of Butte M10 (Figure 12). These cosets are bounded by three sub-horizontal compound-set bounding-surfaces, which are poorly exposed due to regolith cover. Coset 1 (between M10-ID1 and M10-ID2 in Figure 12) is 3.5 m thick and is the thickest observed coset in the Murray buttes area. It contains six cross-sets bounded by subset bounding surfaces. Sets in the upper part of the outcrop have thicknesses between 0.8 and 1.4 m. The cross-laminations within the cross-sets dip at a shallow angle toward the right in Figure 12, indicating an apparent dip toward the north. The subset bounding surfaces that bound these cross-sets dip at a shallower, but observable angle relative to the cross-laminations, with an apparent dip also toward the north. These subset surfaces extend laterally for several meters (measured examples are 5 and 9 m long, respectively). In this section of the outcrop, the subset surfaces are largely planar, with little curvature along their length.

4.4.5.2. Interpretation

The cosets observed on the south side of Butte M10 are some of the thickest observed along the rover's traverse. In dry aeolian systems (sensu, Kocurek & Havholm, 1994), preserved coset thickness is a function of

angle of climb, the wavelength of the migrating dune, but also local scour depth. If the sediment supplied to the depositional system is greater than the amount of sediment leaving, sediment will begin to accumulate and leave behind a record of cross-strata separated by climbing compound-set bounding-surfaces (Rubin & Hunter, 1982). Larger dunes typically have longer wavelengths, and assuming a constant angle of climb (which is typically less than a few degrees (Mountney, 2006) and is difficult to measure using rover data), results in a thicker preserved segment of dune plinth.

Variability in depth of scour in the troughs between bedforms can also lead to an increase in the thickness of the preserved coset (Paola & Borgman, 1991), and depth of scour can be extreme in dry systems where sediment is freely mobile. Paleotopographic depressions can also provide accommodation space in which a thicker coset can be preserved, particularly near the base of the succession (Cardenas et al., 2019). A review of the unconformity mapped by Watkins et al. (2016) indicates that it follows a regional trend: there is no evidence of a paleodepression at this location. Where exposed or preserved at this location, compound-set bounding-surfaces are largely sub-horizontal and do not show any large deviations from this trend that would suggest a deeper level of scouring. The thickness of the cosets (and absence of deep scours) at Butte M10 suggests that the dunes that formed them were relatively large, compared to those which formed the strata observed on the Emerson plateau by Banham et al. (2018), or that the angle of climb was steeper as a result of a decrease of down-wind sediment transport. The thickness of these cosets can be used as a lower bound to estimate the size of the bedforms in the dune field (see Section 5).

4.4.6. Butte M12: Migration of Bedforms and the Morphology of Superimposed Bedforms

4.4.6.1. Description

Butte M12 was viewed from three different sides: north, south, and east. On the south side, cross-laminations and inclined bounding surfaces were mapped across the width of the outcrop (Figure 13a). Here, cross-sets are typically 0.3 to 0.5 m thick and extend laterally for distances of up to 8 m. Cross-sets are composed of the characteristic uniform-thickness, cross-laminations observed elsewhere across the Murray buttes. Annotation of the central section of the outcrop (Figure 13b) shows the presence of inclined subset surfaces that dip predominantly to the left of the outcrop, with an apparent dip toward the west. Most of these subset bounding surfaces have a concave-up curvature forming trough-like features (Figure 13b, red arrow). These subset bounding surfaces, and their associated cross-sets (the cross-set overlying the bounding surface) crosscut and overlie other cross-sets to their right (to the east of the outcrop), and are in turn crosscut by cross-sets to their left (Figure 13b, orange arrow); this stacking arrangement means that crosssets are older on the right side of the outcrop and are younger to the left.

Within the cross-sets bounded by the inclined subset bounding surfaces, cross-laminations display a mixture of left and right-dipping apparent dips: in some cross-sets, the cross-laminations dip in the same direction as the subset bounding surfaces, while others dip antithetically. Some cross-laminations infill shallow troughs (Figure 13b blue arrow). Compound-set bounding-surfaces were not delineated for this outcrop, that is, distinct surfaces where subset bounding surfaces coalesce are identified. Inspection of the east-facing side of the outcrop indicates that the subset bounding surfaces dip at a shallow angle, apparently toward the north, while cross-laminations show shallow dips broadly to the north, although some cross-laminations have an apparent dip toward the south.

4.4.6.2. Interpretation

The inclined subset bounding surfaces, which typically have an apparent dip to the northwest, bound crosssets that are progressively younger from right to left in the outcrop. Each cross-set records the migration of a superimposed dune across the lee-slope of a primary dune (a draa-scale bedform). These successive cross-sets are banked upon the lee slope of the primary dune, giving an apparent migration direction of the dune from right to left (west). The wide variation in apparent dips of cross-laminations, plus the presence of trough cross-lamination, indicates that the superimposed dunes at this location had sinuous-crests, and that their scour troughs were curved as well.

A non-uniform scour depth along the width of a single trough in the lee of each superimposed dune combined with a non-uniform average scour-depth between successive dunes—can lead to complex scour patterns and variable depth of scour of each subset bounding surfaces. Because of this variability of scour

Figure 13. Butte M12, showing complex architectural relations of cross-sets and their bounding surfaces. (a) Uninterpreted view of the south-facing side of Butte M12, oriented between azimuths 079° and 259° . (b) Interpreted view, showing complex geometric arrangement of subset surfaces. Arrows show key features: Red—concave-up curvature of subset bounding surface. Orange—cross-sets with lower subset surfaces cross-cutting features to their right, while being cross-cut by cross-sets on their left. Blue—cross-laminations forming shallow troughs. Mastcam mcam07200, taken on Sol 1455, from end-of-Sol 1454 rover location. Distance to the outcrop was ~12 m.

depth created by superimposed bedforms as they migrated across the primary dune scour (which is also of varying depth along its length), the bounding surface formed by migration of the primary dune (interdune surface) would be overprinted by a complex scour pattern, making the elucidation of that bounding surface difficult.

4.5. Bedform Migration Directions Preserved in the Murray Buttes

The stratigraphy observed at the Murray buttes provides insight into bedform migration patterns that arose as a result of the local wind regime when the Stimson formation sands accumulated. Following the approach of (Rubin & Hunter, 1983), the orientations of cross-lamination and superposition surface dip-azimuths were estimated to provide information about dune transport directions, infer bedform crest orientations, and infer sediment transport direction and how it changed temporally.

4.5.1. Reconstruction of Cross-Set Components Using True Dip Directions at Butte M4

4.5.1.1. Description

Using true dip and dip-azimuth measurements, the intersection line between the dipping cross-laminations and the subset bounding surfaces can be determined, which can be used to estimate the trend or long axis of the superimposed dune's scour trough, which is parallel to the crestline of that dune. The only location at which suitable data to establish this—stereo pair images and perpendicular views to the outcrop faces—was collected at Butte M4.

The north side of the outcrop was imaged in stereo at a distance of 35 m (Figure 9b), which enabled the generation of a digital outcrop model (DOM) of the outcrop. Imaging of the north- and west-facing side of the outcrop allow reconstruction of the true dips of the cross-laminations and the subset bounding surfaces using apparent dip directions.

Using the DOM-derived from the north-facing side of Butte M4, the average dip and dip-azimuth of the cross-bedding was measured to be 19° toward 050° (n = 13), and the subset bounding surfaces 7° toward 000° (n = 11).

A separate method was used to measure the same surfaces and their apparent dips from the near perpendicular north- and west-facing aspects of the outcrop, using MSL rover operations software. This method yielded an average cross-lamination dip and azimuth of 22° toward 017° and a subset bounding surfaces dip and azimuth of 12° toward 309°.

4.5.1.2. Interpretation

These geometric elements can be used to reconstruct the bedform, as done by Rubin and Hunter (1983) and Almeida et al. (2016) for examples on Earth. The geometric elements measured from Butte M4 were plotted on stereonets to determine trend of the superimposed dune scour troughs and bedform crestline orientations. Figure 14a illustrates the orientation and relation of the planes plotted in the stereonets. The superposition surface (subset bounding surface) roughly corresponds (within a compass quadrant) to the dip direction of the primary dune lee slope (the orientation of the primary dune lee-slope will be discussed further in Section 5.2).

The superposition surface (subset bounding surfaces) is a time translatent (four-dimensional) surface eroded by a migrating scour trough in the lee of a superimposed dune, as it migrated across the lee slope of a migrating primary dune. The orientation of the superposition surface is dependent on the migration vectors of the primary and superimposed bedforms. Because of this complex relation, it is difficult to determine the exact orientation of the primary dune crest line. However, it can be estimated. Bedform migration models by Rubin (1987a) suggest that the primary dune migration direction will reflect the superposition surface azimuth, rotated slightly toward the azimuth of the cross-lamination dip direction. The cross-lamination dip-azimuth corresponds to the direction of maximum dip on the superimposed dune's lee surface, which is not necessarily the orientation of the dune crest. The line of intersection of the two planes plotted on a stereo net gives the trend of the scour trough of the superimposed dunes (Figure 14a, red line). The scour trough in the lee of the superimposed dune lee slope will be aligned parallel to the crest of that dune. If an orthogonal line is drawn to the trend of the scour trough (Figure 14a, dashed black lines), this would give an approximate migration vector for the superimposed bedforms.

For the DOM-derived data, the scour trough trends toward 341°, which indicates that the bedforms migrated almost perpendicularly across the lee slope of the primary dune. For the apparent dip method, using the north and west outcrop faces, the scour troughs are interpreted to trend toward 317°, which indicates that the trend of the scour trough roughly coincides with the dip of the primary-dune lee slope. Orthogonal to the trend of the scour trough is the migration direction of the superimposed dune, which suggests that the superimposed dunes migrated almost along the lee slope of the primary dune, toward azimuth 047°.

Figure 14. Reconstruction of bedform migration directions, and map of cross-bedding and subset surface dipazimuths. (a) Stereo nets depicting the geometric relations between the dip-azimuth of the superposition surfaces (orange) and the cross-laminations (white/black). The line of intersection (red) shows the trend of the superimposed dune scour troughs. Orthogonal to the scour trend is the interpreted direction of superimposed bedform migration. (b) Schematic diagram depicting the elements illustrated via the stereo nets in (a). (c) Map depicting true dip-azimuths of cross-laminations at Murray buttes (yellow). The true dip-azimuth of the superposition surfaces within the Murray buttes are depicted in orange. Rose diagrams show the vector mean of the dip-azimuths.

4.5.2. Visual Estimation of Dip-Azimuths Across the Study Area

4.5.2.1. Description

While the accurate measurement of the dip-azimuths can be recorded at Butte M4 using a digital outcrop model, elsewhere in the study area, the dip-azimuth for cross-sets and superposition surfaces can only be visually estimated using the method of Banham et al. (2018), due to distance, lack of stereo coverage, and lack of 3D outcrop coverage (a result of data downlink limitations during the Murray buttes campaign). Although less accurate, this method allows for observation of dip-azimuth trends across the Murray buttes area which can be compared to those at Butte M4. Figure 14a summarizes the true dip-azimuths estimated

Figure 15. Reconstruction of draa-scale bedforms interpreted from the outcrop observed across the Murray buttes area. See text for estimates of bedform height and wavelength. The primary dune lee-slopes are interpreted to dip toward the north. Lee-slope superimposed dunes are interpreted to be migrating roughly toward the northeast, while stoss-slope superimposed dunes speculated from analogs (see text for details).

for cross-laminations and superposition surfaces that record the migration of superimposed bedforms and the primary dunes, respectively.

Visual estimation of 97 representative cross-set dip-azimuths and 25 superposition surface dip-azimuths throughout the Murray buttes shows that bedform migration direction is correlated with the order of the bedform and shares a similar trend to that observed at Butte M4 (Figure 14c).

The vector mean and vector magnitude for the dip-azimuths of the cross-laminations and superposition surfaces were calculated trigonometrically using the method described by Lindholm (1987). Primary dune lee slope dip-azimuths (manifest as the superposition surfaces) show a vector mean of 340°, toward the north-northwest, with a vector magnitude of 0.94. Superimposed dune lee-slope dip-azimuths (approximated by cross-laminations) have a vector mean of 034°, toward the northeast, with a vector magnitude of 0.86.

4.5.2.2. Interpretation

The average dip-azimuths of the cross-laminations and the superposition surface broadly match the trends observed at Butte M4; the superposition surfaces dip toward the northwest, and the cross-laminations dip toward the northeast. If average dips of 11° for superposition surfaces, and 20° for cross-laminations are used to construct a stereo net (Figure 14a, all Murray buttes), an intersection trend of 336° is derived, similar to those at M4. Again, this would suggest that the superimposed bedforms migrated across the lee slope of the primary dunes.

5. Discussion

5.1. Morphology and Dimensions of Formative Dunes Recorded by the Stimson Formation

The compound cross-sets observed in the Murray buttes formed as a result of small, superimposed dunes migrating across the lee slope of a draa (sensu, Hunter et al., 1983): either directly across the lee slope—perpendicular to the crest line—of the draa-scale dune (as demonstrated at Butte M4), or with a preferred along slope component (as indicated at Butte M9c). As the superimposed dunes migrated across the lee slope of the draa, cross-sets generated by the superimposed bedform were preserved in the lower section of the draa lee-slope, as a coset of cross-bedding (Figure 15 (Allen, 1968; Brookfield, 1977; Rubin & Hunter, 1983).

This arrangement of bedforms that generate compound cross-strata—a compound dune—is a commonly observed landform on both Earth (Breed, Fryberger, et al., 1979; Breed & Grow, 1979; Ford et al., 2010; Havholm & Kocurek, 1988; Lancaster, 1982; Sweet et al., 1988) and Mars (Breed, Grolier, & McCauley, 1979; Davis et al., 2020; Fenton, 2020). Superimposed bedforms arise as a result of near-surface boundary layers caused by the presence of the draa-scale bedforms (Rubin & Hunter, 1983; Rubin & McCulloch, 1980); these can be products of surface-wave instability acting on a sufficiently large bed of sand (i.e., the stoss slope) (Elbelrhiti et al., 2005; Lü et al., 2017; Narteau et al., 2009). This instability can initiate dune formation on a flat, dry stoss slope a little over 20 m long (Narteau et al., 2009). These draas are approximately an order of magnitude larger than the superimposed dunes they support (Lancaster, 1988a) and commonly occur in erg centers (Porter, 1986).

Figure 15 shows a sketch that schematically reconstructs the compound dunes recorded by the Stimson formation exposed at the Murray buttes. Although the presence of lee-slope superimposed dunes is recorded in the stratigraphy, there is no recorded evidence for superimposed dunes on the stoss slopes, or their probable orientation. Observations of modern compound dunes, such as those present in the Algodones dune field (Havholm & Kocurek, 1988; Sweet et al., 1988), show that compound dunes can host superimposed bedforms with varying orientations relative to the draa crestline. Here, lee-slope dunes can be oriented perpendicular, while stoss-slope dunes can be oriented obliquely to the draa crest line. Using these analogs, we can infer the presence of stoss-side superimposed bedforms on the draas recorded at the Murray buttes, and speculate that they were oriented oblique to the crest line of the draa, with a potential migration direction between the north and northeast.

Identification of compound cross-sets is the key to interpretation of the correct size of the bedforms. Galeazzi et al. (2018) observed that superimposed bedforms generate cross-sets superficially similar to those created by simple dunes—typically of decimeter thickness. Superimposed bedforms typically occupy a limited size range that is not proportional to their host dune (Galeazzi et al., 2018; Lancaster, 1988b), and misinterpretation of these as simple cross-beds would lead to the assumption that the dunes were much smaller than they actually were.

The original height of compound bedforms is notoriously hard to predict from the stratigraphic record. Determining the angle of climb of the primary dune requires accurate measurement of the elevation profile of the interdune surface; furthermore, the divergence of the resultant transport direction from the dune trend has a bearing on calculating bedform height (Rubin & Hunter, 1985).

A low-level approximation can be made as to the original dune height based on cross-set thickness and coset thickness. The largest unknown is the angle of climb for the primary dune, which controls what proportion of the original dune height is preserved. Aeolian dunes typically only climb at angles of a few degrees (Mountney & Thompson, 2002), and only a small fraction of the original dune is preserved (Mountney & Howell, 2000; Rubin & Hunter, 1982). Without knowledge of the angle of climb, the proportion of the dune preserved cannot be determined, making dune height calculations arbitrary.

However, to give some sense of the primary dune height, it can be hypothesized that the original dunes would have been an order of magnitude higher than the preserved thickness of the preserved coset. In the case of the 4 m thick coset preserved at Butte M10, the draa that produced it could have been roughly \sim 40 m tall. Measurements of the size relations between draas and their superimposed dunes conducted by Lancaster (1988a) suggest that superimposed bedforms can be approximately an order of magnitude smaller than the host draa, suggesting that the superimposed bedforms in the Murray buttes may have been 3 to 5 m high. Assuming that these draas had a bedform index of 15 (Wilson, 1972), wavelengths of 300–600 m could be expected.

5.2. Dune Migration Direction Recorded by the Stimson Formation at the Murray Buttes

Determining the dune migration direction and crest orientation from the stratigraphy preserved at the Murray buttes is complicated, owing to the four-dimensional (4D) interaction of the two scales of bedforms. These attributes can, however, be estimated from the orientation of the cross-laminations and superposition surfaces using stereonets to determine the orientation of the superimposed dune, and by comparison to bedform migration models.

Stereonets were used to determine the trend of the scour troughs in the lee of the superimposed dunes (see Figure 14b for location of scour troughs), where the long axis of the scour trough was oriented toward the north-northwest (between 330° and 340°). The superimposed dune crests form parallel to the axis of the scour troughs, which implies that the superimposed dunes migrated toward the east-northeast (most likely between azimuths 047° and 070°). The axis of the superimposed dune scour trough is oriented approximate-ly parallel to the dip-azimuth of the superposition surface, which suggests that the superimposed migrated across the primary dune lee-slope, with a preferred along-crest component (Figure 15).

Estimating the orientation of the primary dune crest is more difficult, owing to the uncertainties surrounding the relative migration rates between the primary dune and superimposed dunes (Rubin and Hunter, 1983, 1987), and the resulting orientation of the superposition surface in 4D space. Examples of these interactions are given by numerical models computed by Rubin and Carter (2006). Where the speed ratio between the two sets of bedforms are similar, the scour surface forms at ~45° (e.g., Figure 46h of Rubin and Carter [2006]). Where the model depicts superimposed dunes migrating faster than their host dune (e.g., Figure 46k of Rubin and Carter [2006]), the superposition surface scour diverges less from the orientation of the primary dune lee slope. The superposition surface will always be slightly oblique to the primary dune lee slope because the primary dune advances even as the superimposed dune migrates across its lee slope. Based on the stereonet reconstruction, the migration direction of the primary dune (dip-azimuth of lee side) lies between the dip-azimuth of the subset bounding surfaces (dips toward northwest) and the dip-azimuth of the foresets deposited on the superimposed dunes migrated over the primary dune migrated toward this general northerly direction, the superimposed dunes migrated over the primary lee slope with a consistent along-crest component of migration, clockwise of the migration direction of the primary dune, toward the east.

Compound dunes where superimposed bedforms migrate perpendicularly or obliquely to the crest of the primary dune are common on Earth, both in the modern environment (Livingstone et al., 2010; Saqqa & Atallah, 2004) and the ancient record (Rubin & Hunter, 1983). Oblique bedforms have also been noted on Mars, on the lee slopes of the Namib dune in the Bagnold dune field in Gale crater (Ewing et al., 2017) and other examples viewed from orbit (Fenton, 2020).

At the Murray buttes, both allogenic and autogenic processes were likely to be responsible for the formation and orientation of the oblique compound dunes. A multidirectional wind regime likely formed the oblique dunes, and the superimposed dunes would have a different orientation to the primary dunes because they resided within the boundary layer generated by the primary dune.

5.3. Dune Field Construction, Evolution, and Preservation

The processes of aeolian bedform migration and growth tend to thwart the preservation of strata that record the early stages of dune field construction. To some extent, this may be visible in the general vertical succession preserved at the Murray buttes. The early phase of dune field construction is characterized by the generation of protodunes and small dunes, which over time and if sand supply and climate conditions persist, merge to form larger and more widely spaced dunes (Kocurek & Day, 2018). As a dune grows in height, so does the depth of the interdune trough that occurs in the lee of the bedform, which can scour any previously accumulated strata (Kocurek & Day, 2018; Paola & Borgman, 1991; Phillips et al., 2019), removing the record of dune field construction. The lowermost sections of the Stimson formation observed contain the thickest preserved cosets, which would correspond to the largest preserved bedforms (e.g., Butte M9c—4 m thick). This would indicate that the process of sediment accumulation initiated well after the dune field was established. Above the thickest basal cosets, cosets progressively decrease in size with increasing stratigraphic height. This could indicate that bedform size was decreasing over time, if the external sediment supply was decreasing as a result of allogenic factors, or the angle of climb was decreasing due to spatial gradients in the wind, or that over time, the erg was migrating toward the north, and the upper parts of the stratigraphic succession record smaller dunes typically present within the "upwind" back-erg areas (Loope & Simpson, 1992; Porter, 1986).

The absence of super-bounding surfaces (sensu, Blakey, 1988; Kocurek & Havholm, 1994)—that is surfaces formed by episodes of prolonged deflation and erosion—suggests that the succession preserved at Murray

buttes accumulated in a continuous depositional episode, without breaks of deposition that had sufficient length to generate any super surfaces. The Murray buttes succession contains no evidence of fine-grained interdune deposits, or other sedimentary structures and architectural elements associated with hydrody-namic (water-table controlled) sediment accumulation (accumulation of sediment as a result of ground water level—sensu, Kocurek & Havholm, 1994), as also observed at the Emerson plateau Stimson section (Banham et al., 2018). Thus, the architecture observed here suggests that the succession accumulated by aerodynamic mechanisms, resulting in a "dry" aeolian succession characterized exclusively by sandy facies (Kocurek & Havholm, 1994).

5.4. Comparison of the Stimson Formation at the Murray Buttes to the Emerson plateau

This section aims to establish that the Emerson plateau and Murray buttes outcrops record different parts of the same dune field by comparison of their sedimentary facies and architecture, and their occurrence within the stratigraphic succession. The characteristics of the Stimson formation at Emerson plateau were those described by Banham et al. (2018).

Within the stratigraphic succession of Gale, all Stimson outcrops unconformably overlie the Murray formation. The unconformity cuts across > 300 m (Figure 4, Watkins et al., 2016; Banham et al., 2020a) of nearly flat-lying (Stein et al., 2020) Murray formation strata. This unconformity is the base Siccar Point group unconformity. The Stimson formation accumulated directly onto a locally undulating (at meter scale) unconformity surface (best illustrated at Butte M1b—Figure 6) of similar slope and erosional expression as the modern-day exposures of the Murray formation on lower north Aeolis Mons (Watkins et al., 2016).

The facies observed at the two outcrop sites are broadly similar: both areas are characterized by dark gray-colored, weathering- and erosion-resistant, cross-bedded sandstones. In both outcrops, cross-sets are composed of millimeter-thick cross-laminations, which are uniform in thickness along their length (a common attribute of wind ripples) and are laterally persistent for decimetric distances. Cross-set thicknesses at the Murray buttes typically range 0.3–1.0 m (these are usually sets bounded by subset surfaces, in compound cross-beds) that form cosets up to 4 m thick. The similar nature of these fundamental depositional elements suggests that the same depositional process—sediment deposition by wind ripple migration—was responsible for creating the cross-laminations in both areas. Cross-sets at Emerson plateau are 0.4 to 0.8 m thick for decimeter-scale cross-bedding and 0.1 to 0.2 m thick in compound cross-beds. Cosets, or compound cross-sets in the Murray buttes are typically more than twice as thick as the simple and compound cross-sets at Emerson plateau. In both cases, simple and compound bedforms indicate the migration of large aeolian dunes. In both locations, no fine-grained interdune deposits were observed, which would indicate that aqueous processes—such as changing level of the water table—did not influence sediment accumulation.

Architecturally, both outcrops share a common geometric arrangement typical of aeolian successions that accumulated under dry conditions. Both outcrops have laterally extensive bounding surfaces interpreted to be interdune surfaces (dune migration surfaces-Banham et al., 2018; compound-set bounding-surfaces-this study), which can be traced laterally for distances in excess of decameters. Both outcrops also have inclined bounding surfaces relative to these interdune surfaces—here termed subset bounding surfaces. In both areas, subset bounding surfaces interpreted as superposition surfaces have been identified (ubiquitous at Murray buttes, and at Mt. Shields, Emerson plateau), indicating a record of superimposed dunes on the lee side of the primary dunes. The key difference between the two areas is that the Emerson plateau outcrops are predominantly composed of simple cross-bedding-indicating an absence of superimposed bedforms on the lee side of the primary dunes—whereas the Murray buttes expose, almost exclusively, compound cross-bedding. The latter demonstrates that the sandstones at the Murray buttes record superimposed dunes on the lee slides of the primary dunes. If we assume a similar angle of climb for both areas, the increased thickness of the cosets at the Murray buttes compared to the thickness of the cross-sets at Emerson plateau could suggest that dunes which were recorded at the Murray buttes were larger than those recorded at Emerson plateau, however, this cannot be definitively demonstrated. An increased prevalence of larger compound dunes is common within erg centers (Porter, 1986).

The sediment transport direction for both areas is similar (within the same compass quadrant, possibly even the same octant). The sediment transport direction in the Emerson plateau is interpreted to be toward the northeast. The compound cross-bedding can be used to constrain the transport direction for sediment in the Murray buttes area, aided by the divergent bedform migration directions. The superimposed bedforms migrated toward the northeast, while the primary dunes migrated north (or at least, a direction within the northward quadrant). Combining these two orientations suggests that the Murray buttes sediment transport direction was toward the north, or the north-northeast—within the same quadrant as the Emerson plateau transport direction.

From these observations of common attributes—deposition on the same unconformity, facies, sedimentary architecture, and transport direction—a strong case that the two outcrops record lateral variations of the same sand deposit and same depositional environment can be made. The outcrop observed at Emerson plateau—characterized by strata deposited by dunes with simple lee sides—records part of a dune field located toward the erg margin, whereas the Murray buttes—characterized almost exclusively by strata deposited with superimposed dunes on their lee sides—likely records an area closer to the erg center.

6. Conclusions

Our study shows how detailed observations of sedimentary architecture deduced from analysis of rover-derived image data permits reconstruction of complex ancient aeolian landscapes on Mars. We draw the following conclusions:

- 1. The Stimson formation at the Murray buttes is a dark-gray, weathering-resistant, sandstone unit that accumulated as a result of aeolian processes. The sandstones are formed of compound cross-sets containing wind-ripple laminations, and their architectural arrangement indicates that they were deposited by oblique compound dunes. Similar cross-bedded sandstones interpreted to be of the same origin have been observed at Emerson plateau (Banham et al., 2018). Naukluft plateau (Bedford, Schwenzer, et al., 2020); and at the Greenheugh pediment (Banham et al., 2020a).
- 2. Stratigraphically, the Stimson formation at the Murray buttes accumulated on the base Siccar Point group unconformity. This unconformity is interpreted to be an aeolian deflation surface, and down cuts into the underlying lacustrine Murray formation. Within the study area, the unconformity dips from south to north, and preserves 60 m of vertical relief over a distance of ~ 1 km. At the base of the Stimson formation, cross-bed sets are observed to onlap onto the unconformity, where the local relief is high.
- 3. Detailed analysis of the sedimentary architecture shows that the strata are composed of compound cross-bedding, with a hierarchy of bounding surfaces. The hierarchy of bounding surfaces is a relic of various size bedforms interacting, while migrating at different speeds, and in different directions. The largely horizontal compound-set bounding-surfaces that bound cosets are erosional surfaces formed by scour troughs in the lee of advancing draas. The inclined subset bounding surfaces that bound cross-sets are interpreted to be superposition surfaces formed by migration of smaller superimposed dunes across the lee slope of the draa. Cross-sets between subset bounding surfaces are depositional packages that accumulated on the lee slope of the draa. Finally, cross-laminations record deposition of wind-blown sand on the lee-slope of the superimposed dunes.
- 4. Analysis of the cross-lamination and subset bounding surface dip azimuths allowed an accurate reconstruction of the bedform geometries. In general, across the Murray buttes, the vector mean of cross-lamination dip-azimuths is toward 034°, while the vector mean of the superposition surfaces is toward 340°. The scour pit trends were oriented toward 336°, indicating that the superimposed dunes migrated in a direction parallel draa crestline, toward the northeast. The draas migrated toward the north.
- 5. Reconstruction of compound bedforms is difficult without knowing the angle of climb, but speculating that the original dunes were an order of magnitude higher than their preserved cosets, primary bedforms can be estimated to have been 20 to 40 m tall, with wavelengths of 300–600 m. The superimposed bedforms could have been around 2 to 4 m high, with a spacing of ~60 m.
- 6. Comparison of the Stimson formation outcrops observed at the Murray buttes and the Emerson plateau indicates that the two outcrops record spatial variations within the same depositional system. Depositional processes recorded by sedimentary facies and architecture are identical between the two locations. The main difference is that thicker (up to four times thicker) compound cross-sets are observed at the

Murray buttes. This indicates that the Stimson formation at the Emerson plateau was probably deposited by smaller simple aeolian dunes, whereas the Murray blower uttes records larger compound aeolian dunes. The latter are typically more common toward an erg center.

Data Availability Statement

The data used during this study are publicly available on the NASA Planetary Data System, via the MSL Analyst's Handbook, or the PDS image Atlas (https://pds.nasa.gov/datasearch/data-search/). Image products data generated by this study are provided as an additional resource via the Zenodo open access repository – Banham, Gupta, Rubin et al. (2020). This includes: a slide pack containing figures, data sources, and additional maps, provided as a teaching resource; a GIS data set for the Murray buttes area showing the location of buttes, field-of-view for the mosaics used, and the transport directions. Finally, a slide pack of figures, images, and additional diagrams associated with this study have been included as supporting information. This material is intended for teaching, outreach, or further research.

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