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► To cite this version:

Amelie L. Roberts, Sanjeev Gupta, Aster Cowart, Lauren Edgar, William E. Dietrich, et al.. Depositional processes and environments of the Layered Sulfate-bearing unit, Gale crater, Mars. Tenth International Conference on Mars 2024, Lunar and Planetary Institute, Jul 2024, Pasadena (California), United States. pp.3515. hal-04650564

HAL Id: hal-04650564

<https://hal.science/hal-04650564v1>

Submitted on 16 Jul 2024

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Depositional processes and environments of the Layered Sulfate-bearing unit, Gale crater, Mars

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Introduction: From orbit, a shift from clay-bearing to sulfate-bearing stratigraphy is recorded in the layered sedimentary rocks of the central mound of Gale crater [1]. This transition potentially records a shift from wet to dry conditions as seen from orbit elsewhere on Mars [2]. The Mars Science Laboratory *Curiosity* rover can test these hypotheses *in-situ*. Here, we describe the sedimentary facies and architecture within the sulfate-bearing strata exposed in Marker Band valley and Gediz Vallis explored by *Curiosity* between Sols 3560 to 3917 (elevations -3880 to -3775 m) to interpret their depositional processes and environments.

Stratigraphic context: The clay-bearing stratigraphy, found in the Murray and Caroline Shoemaker formations, was predominantly deposited in aqueous palaeoenvironments [e.g. 3, 4]. So far, *Curiosity's* exploration of the overlying clay-sulfate transition, within the Mirador formation, reveals a transition to aeolian deposits [e.g. 5; 6] with intermittent aqueous activity [7].

Marker Band valley transitions into Gediz Vallis and is eroded into the sulfate-bearing strata. The stratigraphy here is subdivided into the (1) Contigo, (2) Catrimani, (3) Amapari, and (4) Chenapau members of the Mirador formation (Fig. 1).

Unit architecture: Here, we summarise the ~70 m of vertical stratigraphy exposed in Marker Band valley (Fig. 1) which we subdivide into 11 units labelled A through K (Fig. 1) which remain broadly, laterally consistent across the study area: ~1 km².

The strata exposed at the base of Marker Band Valley comprises the upper part of the Contigo member. Here Unit A (>8 m thick) is characterized by m-scale sets of low-angle (apparent angles of 5-6°) cross-stratification with sharp, planar bounding surfaces. This is sharply overlain by the Catrimani member, Unit B (~5 m to ~15 m thick [2]), characterized by planar stratification. Between the Catrimani and Amapari members is a light-toned, mottled unit (Unit C; ~0.5 m thick) with a lower contact that penetrates into the underlying strata by a set of converging inclined fractures creating a saw-tooth pattern [also see 8]. This unit is sharply overlain by the Amapari member (Unit D; ~1 m thick) containing a dark-toned, indurated band (~0.5 m thick) seen from orbit [9] and a recessive component (~0.5 thick).

This is sharply overlain by the Chenapau member (>35 m thick) composed of dark- and light-toned stratigraphic sections which we have subdivided into 7 units, E through K. Units E (~3.6 m thick), G (2.7 m thick), I (~4.9 m thick), and K (>7.8 m thick) are slope-forming and appear mostly structureless from afar but occasionally preserve evidence of planar stratification. Units F (~4.2 m thick), H (~5.3 m thick), and J (~7.3 m thick) appear dark-toned and scarp forming. These characteristics are visible from orbit. Unit F contains localized corrugated textures and north-dipping bands. Units H and J are characterized by planar interstratified resistant bands with recessive strata sets which create shadows giving the dark-toned appearance. Truncation of low-angle sets are seen in Unit J.

Embedded within the stratigraphy of Unit E, there is an indurated, dark-toned asymmetric, lens (~7 m x ~0.5 m) which pinches out laterally in a 'wing-shape'. Between units H and I, a set of nine distinct, broad, concave-up scour-and-fill structures (~60 to ~40 m x ~1 to 4 m) are observed. The scours are simple, symmetric, with occasional planar bases, infilled by onlapping light-toned strata characteristic of Unit I. An additional scour truncates into Unit J and is overlain by Unit K.

Description of nearfield facies observations: Unit A is characterized by dark-toned bands separating recessive laminae consistent with the thicknesses of the inclined cross-strata. Bounding surfaces with associated asymptotic cross-laminae were identified along the traverse. Unit B is characterized by a facies with light-toned, planar, uniform, laterally extensive laminae (~0.74 mm thick). Both Units A and B are overprinted by <1 mm thick nodules obscuring grain size. In Unit C, a DRT underlying the Marker Band indicates a softer texture with mottled red, white, and green coloring. Unit D consists of a symmetric rippled and a thickly laminated component [6, 9, 10, 11].

The base of Unit E is sharp, overlain by strata with undulations (~50 cm in wavelength) and an abrupt change into a massive-appearing horizon composed of irregularly-shaped nodules that become planar up-section. The infill of the dark-toned lens within unit E consists of amalgamated bedsets of centimeter-scale tabular cross-stratification dipping to the north-west. Unit F is characterized by sets (~5-14 cm thick) of corrugated

textures composed of wavy laminae which resemble climbing, asymmetric ripples. These have amplitudes of <1 mm and vary in wavelength by 4-8 cm. Units G through K have repeating facies associations. Units G, I, and K are all characterized by uniform, planar, laterally extensive, ~0.76 mm thick laminae. Each individual laminae preserves either a light-toned and dark-toned component (Fig. 2) creating a pin-stripe pattern. Units H and J are characterized by the gradual introduction of dark-toned, indurated, laterally discontinuous laminae which break up the uniform, planar, light-toned laminae into 12 – 1 cm thick sets. These dark-toned laminae have a smooth surficial texture and protrude out of the rock as elongated, parallel fins, spaced ~4-5 cm apart. Units H and J are associated with abundant, small disc-shaped features and more angular nodules.

Stratigraphic synthesis and implications: The transition recorded from Units A through D is interpreted to represent a shift in environment from the predominantly aeolian dune setting recorded in the clay-sulfate transition region. The cross-strata of Unit A is the preserved expression of migrating, simple dunes. The dark-toned bands are interpreted as preferential diagenesis from changes in grain size and sorting associated with dune depositional processes [12]. The extent, uniformity, and planar expression of the laminae are characteristic of the migration of wind ripples in an aeolian sand-sheet environment where dune formation was inhibited by near-surface water [e.g. 13]. The mottled texture, red/white coloring and fracture morphology of Unit C are consistent with terrestrial exposure surfaces [7, 14]. The facies of Unit D are consistent with lacustrine environments [e.g. 6, 9, 11, 12].

The sharp contact of Unit E represent a transition into a distinct environment. The dark-toned lens within Unit E with the asymmetric central body, wing-shaped features, and cm-scale amalgamated bedsets of tabular cross-stratification are consistent with fluvial erosion and infill [15, 16]. Fluvial scouring indicates Unit E must have occurred in a subaerial environment.

Units F through K represent a return to a sand-sheet environment. Even though both aqueous and aeolian wind-ripples climb [12, 17, 18], the wide-spacing and small amplitudes of the corrugations in Unit F are consistent with wind-ripples [e.g. 17] potentially indicating a comparatively higher sedimentation rate and lower wind energy [e.g. 18]. The clear pinstripe pattern seen in Units G, I, and K caused by changes in tone [e.g. 19] and cementation [e.g. 20] are distinct to wind-ripple migration in a sand-sheet environment (Fig. 2). The dark-toned bands in units H and J may represent preferential cementation or diagenesis from a change in grain-size, pore size, or pore space.

The geometry of the scours with broad cross-

sectional concave profiles, flat central portions, and similar facies outside of and within the scour-and-fill structures suggest that the scours likely formed by aeolian processes. We interpret that the scours likely represent saucer-shaped aeolian ‘blowout’ structures [e.g. 18] formed by deflation from intense winds.

Overall, the sedimentary structures found in the layered sulphate-bearing strata in marker band valley represent a predominantly ‘dry’ aeolian environment with intermittent high winds causing blow-out structures and a thick succession of sand-sheet strata. The sand-sheets show that there was likely sustained, near-surface water during the accumulation of the layered sulfates.

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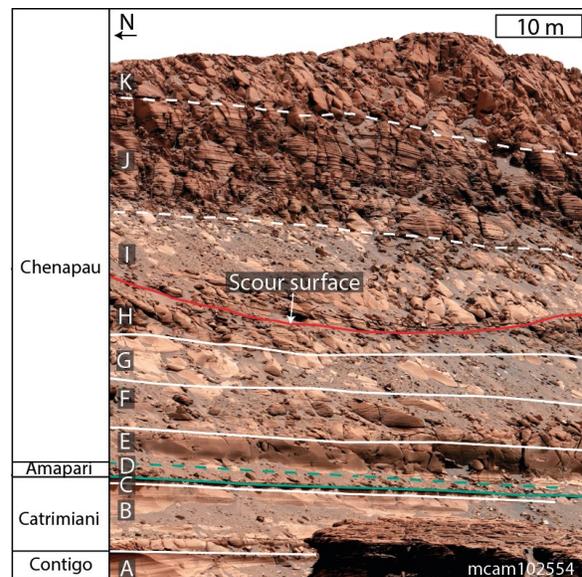


Fig. 1: The stratigraphic units as seen in one of the buttes in Marker Band Valley featuring one of the broad, concave-up scours. Image credit: NASA/JPL-Caltech/MSSS.

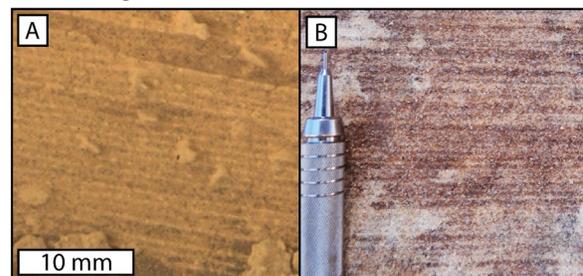


Fig. 2: A) Pinstripe pattern in laminae taken by the Mars Hand Lens Imager (MAHLI) on sol 3866. Image credit: NASA/JPL-Caltech/MSSS. B) Terrestrial pinstripe laminae from wind ripple [from 19].