

Stratigraphic Partitioning of Evaporites Through the Clay-Sulfate Transition in Gale Crater, Mars



Key Points:

- The 210-m-thick clay-sulfate transition records eolian environments with intervals of distinct wet or damp deposition
- Mg/Ca-sulfate enriched nodules are linked to intervals with a near surface water table and consistent with early diagenetic formation
- Sediment accumulations and deflations resulted from climate modulated saline water table fluctuations

Supporting Information:

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

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Abstract Changing surface conditions on Mars during the Hesperian eon (~3.6–3.0 billion years ago) produced widespread stratal sequences transitioning from clay to sulfate-bearing according to orbital data. Using data collected in situ at Gale crater by the Curiosity rover, we examined both the sedimentology and geochemistry of a 210-m-thick succession across a reference clay-sulfate transition. Four intervals (A–D) are defined based on both sedimentary structures and nodule distribution and composition, reflecting changes in depositional setting and diagenetic parameters. Large trough cross-beds, which become prevalent within interval A and dominate intervals B and C, are interpreted to indicate eolian processes, whereas dark-toned lens-shaped sandstone bodies in interval C point to recurring fluvial incursions. Planar bedding in uppermost interval D suggests damp or wet interdune conditions. ChemCam analyses show nodules are enriched in calcium and magnesium sulfates. The highest observed nodule densities coincides with strata interpreted to reflect damp or wet depositional environments (A, C, D), whereas their near-absence corresponds to the interval interpreted as the driest (B). We propose that this stratigraphic partitioning of the type, density, and sulfate-content of nodules indicates that they mostly formed during early diagenesis via capillary evaporation in the shallow subsurface, with only subordinate late-stage remobilization. The preserved strata record fluctuations in water availability and sediment supply, driven by repeated changes in climate, rather than by a single drying trend. These observations suggest new constraints on the fate of sulfur on early Mars and sulfate evaporite formation within sedimentary basins.

Plain Language Summary During Mars' Hesperian period (~3.6–3.0 billion years ago), changing environmental conditions produced widespread sedimentary rock sequences that transition from clay-rich to sulfate-rich deposits as observed from orbit. Using data from NASA's Curiosity rover, we examined a 210-m-thick sequence of these sedimentary rock in Gale crater, analyzing their sedimentary structures and chemical composition. Structures formed by wind-blown dunes dominate much of the section, but we also identified evidence of ancient rivers and damp environments. We find that within the sedimentary bedrock, nodules—enriched in calcium and magnesium sulfates—formed by saturation of salty water within the sediment. The highest concentrations of these nodules occur in layers associated with wetter conditions, while their near-absence is found in the drier periods. Our findings suggest that these nodules formed primarily by evaporation in the sediment at shallow depth below the ancient surface of deposition, rather than more recent infiltration through the sedimentary rock sequence. The preserved sequence record repeated fluctuations in water availability and sediment supply, reflecting a dynamic climate history rather than a single drying trend. This work provides new constraints on the formation of sulfate evaporites in Mars' ancient sedimentary basins and the evolution of its climate.

1. Introduction

Thick sulfate-enriched stratal sequences have been identified globally on Mars from orbit. These successions have been primarily observed in Hesperian aged terrains (3.6–3.0 Ga) and linked to volcanic resurfacing, and have been hypothesized to have resulted from global desiccation (Bibring et al., 2006). Yet, based solely on orbital data, the processes that led to these major sulfate deposits remain elusive. At Gale crater, the Curiosity rover has explored the slopes of Aeolis Mons (informally named Mt. Sharp), providing the first ground-based opportunity to directly examine a kilometer-thick, sulfate-enriched succession that may be comparable to other sulfate-bearing facies identified globally (Grotzinger & Milliken, 2012).

The lowermost section of Aeolis Mons is dated to about 3.6 Ga (Le Deit et al., 2013) and exhibits orbital spectral absorptions attributed to clay minerals. It transitions upward to layered sulfate-bearing deposits over hundreds of meters of stratigraphy (Fraeman et al., 2016; Milliken et al., 2010; Sheppard et al., 2021). Because of their relevance for Mars global stratigraphy, investigating environmental settings associated with these secular changes in mineralogy is one of the primary objectives of the Curiosity rover mission (Vasavada, 2022). The rover traverse across the transition region has provided a wealth of new data on the sedimentology and geochemical composition of the strata in this key transition interval.

Below the transition to sulfate-bearing strata, the succession of the Mt. Sharp group is consistent with wet depositional environments. The lowermost unit of this group, the Murray formation, is dominated by lacustrine mudstone (Grotzinger et al., 2015; Schieber et al., 2022; Stack et al., 2018) with occurrences of very fine sandstone and heterolithic facies which also include both intermittent sulfate enrichment and variable clay mineralogy, reflecting shallow-water depositional settings, such as lake margin and evaporitic environments (Bristow et al., 2018; Gasda et al., 2024; Rapin et al., 2019; Schieber et al., 2024). Higher in the Murray formation, strata observed at the Vera Rubin ridge and the base of the clay-bearing Glen Torridon area are dominated by finely laminated mudstone (Bennett et al., 2023; Dehouck et al., 2022; Edgar et al., 2020) and a diversity of small nodules; sulfate cement is present in low concentrations (Gasda et al., 2022). Intercalated mudstone and sandstone in this interval indicate a sustained lacustrine deposition, alternating with fluvial and lake margin settings (Caravaca et al., 2022; Cardenas et al., 2023; Edgar et al., 2020; Fedo et al., 2022; Thorpe et al., 2022).

The onset of the transition from clay to sulfate-bearing strata lies above Glen Torridon and can be identified by features observable from both orbital and in situ data. Both Ca and Mg-sulfate have been found by Curiosity as bedrock enrichments, and Ca-sulfate is also commonly identified in fracture-fills (Rapin et al., 2016). However only absorption attributed to Mg-sulfate are observed in orbital data. The lack of observable Ca-sulfate absorptions from orbit is likely due to dehydration and their limited aerial extent (Sheppard et al., 2021; Vaniman et al., 2024). Assessment of the data in the lowermost part of the transition (Meyer et al., 2024) identifies a regionally distinctive morphological scarp that is associated with a low-angle unconformity that separates lake margin deposits from overlying eolian strata (dashed line in Figure 1). The scarp also marks a slope break in the Aeolis Mons topography, with steeper butte-forming strata upsection. Sulfate-enrichment becomes apparent near this scarp, below and above, in the form of erosion-resistant nodules of variable prominence and lithology (Meyer et al., 2024; Rapin et al., 2023; Seeger & Grotzinger, 2024). The transition above this scarp also exposes strata in which orbital spectral absorptions indicate the presence of polyhydrated sulfates (Sheppard et al., 2021). In situ analysis of bedrock drilled samples above this scarp by X-ray diffraction indicates the absence of clay minerals contrasting with underlying strata (Rampe et al., 2023). At the top of the transition region, upon entering into the sulfate-bearing unit as identified from orbit, drilled sample also revealed the presence of crystalline Mg-sulfates for the first time on Aeolis Mons (Chipera et al., 2023; Clark et al., 2024). The mineral assemblages of drilled samples into subsequent strata of the sulfate-bearing unit above also include variable proportions of kieserite and polyhydrated Mg-sulfates such as starkeyite alongside siderite (Burt et al., 2024; Tutolo et al., 2025). Most of the observed sedimentary structures in the transition interval are large scale cross-beds that suggest a dominantly arid and eolian environment of deposition (Meyer et al., 2024; Rapin et al., 2021), although isolated lenses and strata also locally show intermittent fluvio-lacustrine conditions (Mondro, Fedo, et al., 2025; Roberts et al., 2026).

The processes responsible for sulfate deposition in the transition interval and above into the sulfate-bearing unit are key to understanding both the paleoenvironments within Gale crater, as well as the fate and potential cycling of sulfur in sedimentary basins across the Hesperian eon. A key question regarding sulfate deposition lies in the timing of formation. Proposed scenarios include (a) schemes where the sulfate enrichment for this interval relies largely on late stage diagenesis (Meyer et al., 2024; Seeger & Grotzinger, 2024), and (b) localized early diagenetic

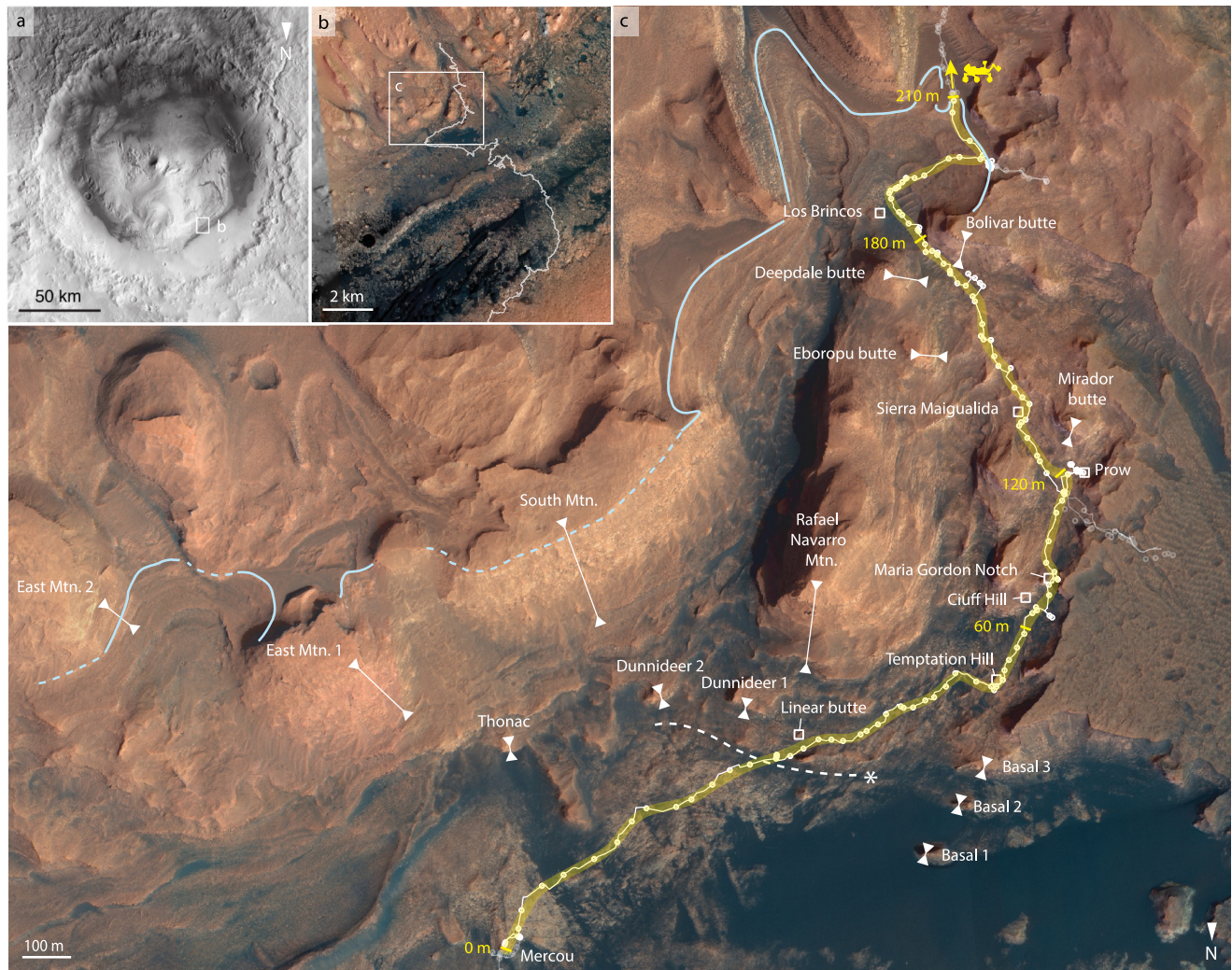


Figure 1. Context of Aeolis Mons stratigraphy in Gale crater (a) with local HiRISE map (b and c) showing Curiosity rover traverse (shaded yellow) across the transition zone from clay to sulfate-bearing strata (Sheppard et al., 2021) between Mercou (elev. 0 m or $-4,070$ m MOLA) and up to the sulfate-bearing unit and the marker band (elev. 210 m). Distinctive stratigraphic boundaries are indicated with the regional scarp boundary near the base (dashed white line and *) (Meyer et al., 2024) and the Marker Band at the top (blue line). Circles indicate the location of rover stops between drives where images and chemical data were acquired. The location of buttes at distances less than 40 m (squares) as well as long distance exposures (triangles) is also shown with stratigraphic thickness covered used in the following figures (see Figures 2 and 7–9). Credit: NASA/JPL-Caltech/University of Arizona.

enrichment due to evaporitic conditions here and in underlying strata (Rapin et al., 2019, 2023; Schieber et al., 2022, 2024). In this contribution we finely reconstruct the stratigraphic record by analyzing rover data to log sedimentary structures and examining associated sulfate enrichment. We expand on the stratigraphic succession analyzed by Meyer et al. (2024) and include long distance imaging (up to kilometer scale) to explore the lateral extent of key sedimentary structures. Such analyses on both the stratigraphic architecture and distribution of sulfate enrichments, constrains possible formation scenarios, including subaerial evaporation from a fluctuating water table.

2. Materials and Methods

We use both chemical analyses and imaging from the Curiosity rover as it ascended Aeolis Mons into the sulfate-bearing unit (Figure 1) to describe and document details of the stratigraphic record in this transition, and provide virtual graphic logs (Bristow, 2020). The interval covered here starts on sol number 3088 at the base of the transition interval and ends on sol number 3642 with the arrival at the Amapari Marker Band contact, a distinctive regional dark-toned horizon of the Mt. Sharp group (Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025;

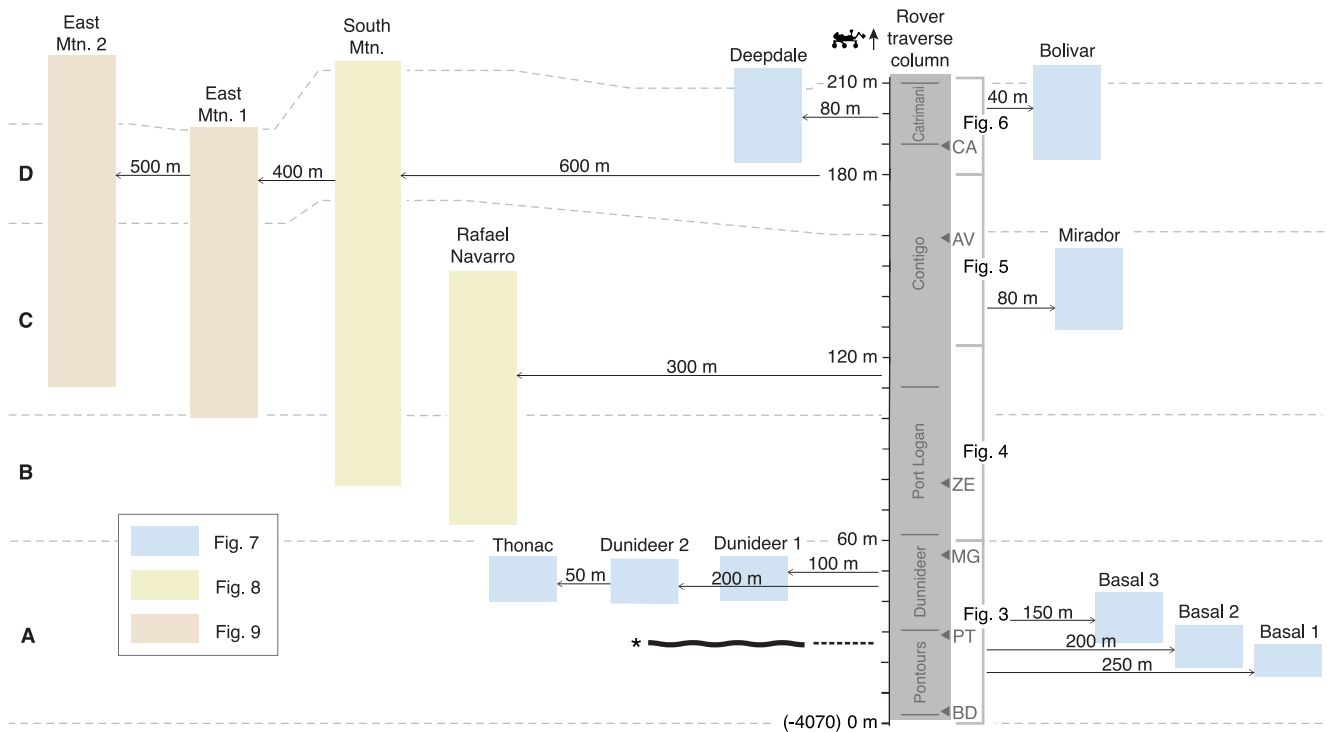


Figure 2. Layout of stratigraphic sequence with observable intervals (A–D) on buttes in the distance (colored columns) relative to the rover traverse (grey column). The layout points to 4 main figures describing sedimentary structures at close distance (less than 40 m, Figures 3–6) and 3 other figures for mid-distance buttes (observed from 40 to 250 m, Figure 7) and longer distance (300 m–1.5 km, Figures 8 and 9). *Regional unconformable contact in interval A (Meyer et al., 2024). The location of drill samples is annotated with two letters abbreviation (BD = Bardou, PT = Pontours, MG = Maria Gordon, ZE = Zechstein, AV = Avanavero, CA = Canaima).

Weitz et al., 2022). Compared to terrestrial methods, use of Mars rover data for stratigraphy induces specific biases. Most critically, the rover path is restricted to traversable terrains of limited slope and roughness, and detailed analyses are performed only at discrete locations separated by drives of tens of meters. This progression can preclude a continuous understanding of stratigraphy depending on exposure quality and the scale of features being assessed. The stratigraphic interval covered here has a thickness of 210 m investigated from 148 rover locations distributed across 3.85 km laterally (Figures 1 and 2). Elevation gains between rover locations typically amount to 1 m or less, though gains of up to 6 m occur in places. Such jumps in coverage, combined with variable exposure quality due to talus, regolith cover, and windblown sand, only allow for compilation of a partial stratigraphic column, with scattered meter scale gaps. To avoid missing important features, imaging of well exposed slopes of distant buttes have been included to this survey. Doing so also added an important lateral dimension to the assessment of sedimentary structures and stratigraphic architecture.

At the smallest scale we used the ChemCam instrument Remote Micro Imager (RMI) combined with sub-millimetric analysis of elemental composition on each target by Laser Induced Breakdown Spectroscopy (LIBS) (Maurice et al., 2016). The sampling size of ChemCam LIBS at ~0.5 mm implies that its measurements are sensitive to sand-sized heterogeneities (Rivera-Hernández et al., 2020). It is possible to infer grain size from such variability by assuming compositional (chemical) heterogeneity of grains, where in case of a sandstone, successive ChemCam laser ablation spots may show stronger differences in composition than if a mudstone was targeted. Yet, if a mudstone with disseminated salt crystals or sand size cemented regions were to be sampled with ChemCam LIBS, it may display heterogeneity comparable to a sandstone target (Schieber et al., 2024).

Each ChemCam target is analyzed on 5 points forming a line across an adjustable distance up to a couple of centimeters, providing the composition on lithological features down to millimeter scales. We classified ChemCam targets based on context to sort out bedrock from soils or float rocks, which could not be attributed to stratigraphy. Each bedrock target is then attributed to one of 3 categories depending on lithology: (a) “host bedrock” exhumed with smooth texture, (b) “mm-scale nodular bedrock” showing nodular features of millimeter-

scale and (c) “cm-scale nodular bedrock” with erosion resistant nodular features that can protrude up to several centimeters from the host bedrock (Figure S1 in Supporting Information S1).

ChemCam is uniquely suited to document the composition of nodular features. Their uneven surface and variable size, from millimetric to centimetric, has prevented drill sample acquisition (for CheMin X-ray diffraction analysis or SAM evolved gas analysis) and limited compositional measurements by the arm mounted APXS instrument. To compensate for this shortcoming, ChemCam LIBS data have been acquired on a variety of nodular targets. In addition to the major oxides routinely quantified using the methods described by Clegg et al. (2017), ChemCam is also able to measure sulfate abundance above a ~ 10 wt.% SO_3 limit of detection (Rapin et al., 2019). The only other instrument sensitive to the composition of targets with high surface roughness is Mastcam via multispectral analysis, yet multispectral data is often hampered by dust coverage and sediment mixtures within host bedrock, which tend to obscure sulfate signature within Mastcam multispectral range (Eng et al., 2024). ChemCam LIBS also documents fractures and vein fills at submillimeter scale discriminating their chemical signature from host bedrock. These dark-toned and light-toned veins, also identified in prior work (Meyer et al., 2024; Seeger & Grotzinger, 2024), have been effectively sorted out from the host bedrock data set in order to separate material of the sedimentary matrix from these late-stage post-lithification features. The classification of the data set was made consistent with other published data on this interval.

The distribution of nodules and nodular textures was logged in stratigraphic columns along with sedimentary structures (Figures 2–6). We completed the graphic logs at a scale of 1:250 using Mastcam images of outcrops in the rover workspace, covering the immediate vicinity a few meters in front of the rover. Outcrops at mid-distance up to 45 m away are also included, but these are represented with partial features and as lateral equivalent to the main log since nodular textures are poorly resolved at this distance (pixel size of up to 9 mm on target). The presence of nodules is annotated on graphic logs only where these textures can be resolved, depending on distance and lighting conditions. To mitigate this observation bias, we mapped the density of centimetric nodules along the stratigraphy using Mastcam images of the workspace acquired by the rover at each stop. Workspace imaging provides systematic images of bedrock with similar lighting conditions and viewing angle. We assessed qualitatively the presence of centimetric nodules hosted in bedrock, on average for each workspace, in 4 groups: absence, low, medium and high density (Figure S2 in Supporting Information S1).

At the largest scale we observed sedimentary structures on well exposed slopes up to 1.5 km away (Figures 7–9). Mastcam images were used for context on distant outcrops, as well as ChemCam RMI which provides a resolution of a few centimeters on targets 500 m away (Le Mouélic et al., 2015), sufficient to observe some sedimentary structures from sloping exposures not accessible directly by the rover (Figure 1). Graphic logs at 1:1200 were positioned in elevation next to each other using a digital terrain model to facilitate lateral correlations (Figure 2). The terrain model available for the Curiosity traverse uses stereo imaging from the HiRISE instrument onboard the Mars Reconnaissance Orbiter, allowing for vertical resolution of 1 m, sufficient for stratigraphic analysis at this scale (Calef & Parker, 2016). The positioning of logged sedimentary features on the column was based on registering their location as observed in Mastcam images on the terrain model in order to determine their elevation. To integrate long distance observations with those from proximal and mid-distance locations, the 4 original sections of graphic logs compiled at 1:250 were assembled and synthesized into a single column at 1:1200 correlated with hillside exposures elevations (Figure 2).

3. Results

We identified 4 distinct stratigraphic intervals along the rover traverse. Each of these intervals (A to D; Figure 2) is differentiated on the basis of sedimentary structures, bedrock lithology, and broader geologic setting. Major sedimentary structures and associated lithologies are described below, followed by nodular textures and composition, and a summary of the intervals in ascending order.

3.1. Sedimentary Structures

Within the stratigraphic succession we identified and present here 3 major types of sedimentary structures, including their lateral variability and associated outcrop lithology.

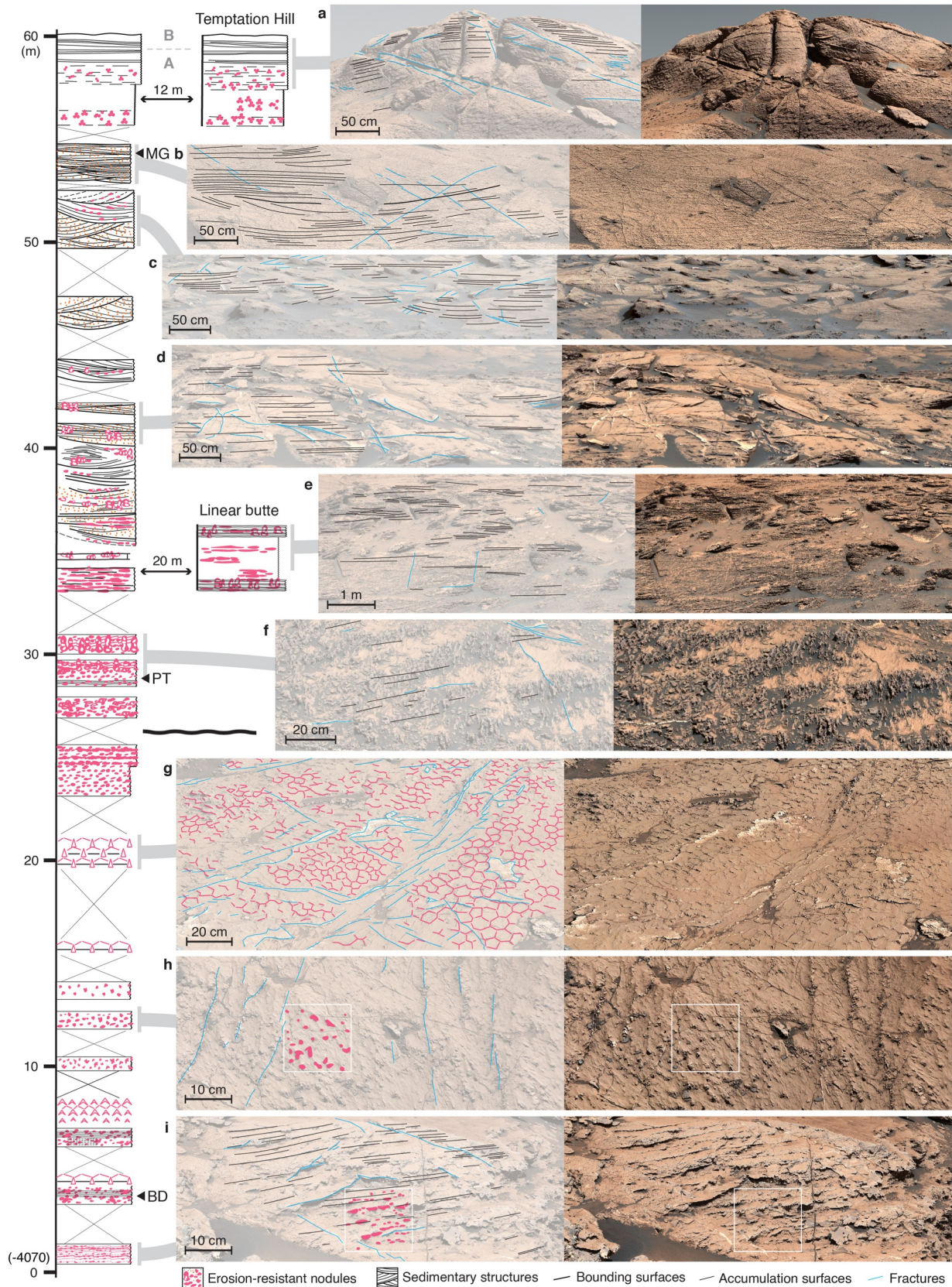


Figure 3.

3.1.1. Large Scale Trough Cross-Bedding

The dominant type of bedding observed across intervals A, B and C is meter to decameter-scale cross-stratification with trough-shaped lower bounding surfaces. It is identified by concave-up bedding shapes forming sets with tangential lower contacts onto trough surfaces. These bounding surfaces and their cross-cutting relationships with underlying sets can be identified on multiple outcrops at short to middle distance (Figures 3b, 4f, 4h, and 5e), yet due to their large scale these sedimentary structures are best expressed on larger outcrops exposed on buttes in the distance (Figures 7e, 8d, 8f, 9b, and 9c). The thickness of sets appears variable across the stratigraphy, with sub-meter sets in interval B (Figure 8g) and up to 5 m thickness in interval C (Figures 7e and 9c). Measuring thickness is difficult due to the uncertainty of identifying bounding surfaces on these exposures. Low-angle cross-bedding also occurs intermittently in the lower intervals A and B (Figures 3d, 3e, 4e, 4g, and 4h). These two intervals are observed in the lower section of large buttes, and long-distance observations show only poorly exposed outcrops due to scree and regolith cover. There is evidence for cross-bedding (Figure 8g), but the rarity of exposures may reflect intimate interbedding with planar bedded sets, as observed at short distance by the rover (Figures 3a–3e and 4g–4i). In interval C, where large cross stratification is best expressed, more diverse bedforms are observed with convex-up shapes, isolated groups pinching-out laterally (Figure 8d) and more complex assemblages with cosets of smaller scale cross-bedding (Figures 8f, 9b, and 9c).

3.1.2. Small Scale Lens-Shaped and Cross-Stratified Troughs

Within interval C are dark-toned, elongated sediment bodies with internal sedimentary structures. Because of their resistance to erosion, they project out of the softer host bedrock, forming distinctive benches that are either lens-shaped concave-up or irregular, and meters to decameters in width. These lenses are hosted by large-scale trough morphologies (e.g., Figure 8c). Their basal contacts are generally sharp and erosive and may be either concave-up forming lenses (Figures 4a, 5i, 8c, and 8e), or irregular with wavy elongated shapes (Figures 4b, 5g, and 5h). Though usually isolated, some lenses are grouped into amalgamated compound structures (Figures 7e, 7f, and 9e). Lenses are asymmetrical with at least one end pinching out or both ends terminating laterally (Figures 8c, 8e, and 8f). Internally they consist of submeter to meter-scale, amalgamated sets of compound cross-stratified sediment (Figures 5j and 7f), with some lenses observed to form steeply dipping (~ 10 – 15°), parallel to sigmoidal bedforms (Figures 8e and 9e). Other localized internal stratification styles include tabular low-angle cross-stratification (Figures 5g, 5i, and 8c) and wave ripple lamination near the top of lenticular sediment bodies (Figure 4a) (Caravaca et al., 2025; Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025).

3.1.3. Planar and Subplanar Bedding

Planar to subplanar bedding is found intermittently within horizons of interval A and B and then becomes prevalent in interval D. Near 25 m elevation, long distance observations indicate parallel planar beds above a major contact marked by fractures and vein networks (Figures 7j, 7k, and 7l). Planar to subplanar strata observed upsection can show comparatively dense nodular overprinting (Figures 7g and 7h), as well as smooth laminated texture (Figures 4e and 4i). In interval D, planar bedding is found throughout and associated with nodular textures that either enhance laminations (Figures 5a and 6c) or are spread more uniformly (Figure 6d). Planar laminations can be somewhat wavy and may also thin out or crosscut at low-angle (Figures 6b and 6d). At the top of the interval, planar beds are truncated by the regional Amapari Marker Band surface as observed on distant outcrops (Figures 8a and 9d) and consistent with prior observations (Rapin et al., 2021). This sharp contact is underlain by a 10–50 cm thick dense nodular horizon (Farrand et al., 2025) that obliterates sedimentary structures (Figures 6a and 7a–7d).

Figure 3. Stratigraphic section from 0 to 60 m elevation (−4,070 to −4,010 m relative to the zero-elevation datum). This lowermost interval includes the transition into the Mirador formation with a contact near 26 m elevation (−4,044 m) (Meyer et al., 2024). Bedrock hosts a variably dense nodular texture, overprinting the contact and sedimentary structures up to the top of interval A at 60 m elevation. Nodular textures are highlighted (red) on examples (white boxes). Occurrences of mill mm-scale nodules are reported as well (orange dots). As observed on images (right) they show diverse lithologies across this stratigraphy, including a pattern of polygonal ridges (g) modified after (Rapin et al., 2023). Includes drill samples PT and MG (Figure 2). Image identification: mcam100694 (a), mcam100502 (b), mcam100678 (c), mcam100688 (d), mcam100629 (e), mcam100383 (f), mcam100270 (g), mcam100232 (h), mcam100038 (i). Credit: NASA/JPL- Caltech/MSSS.

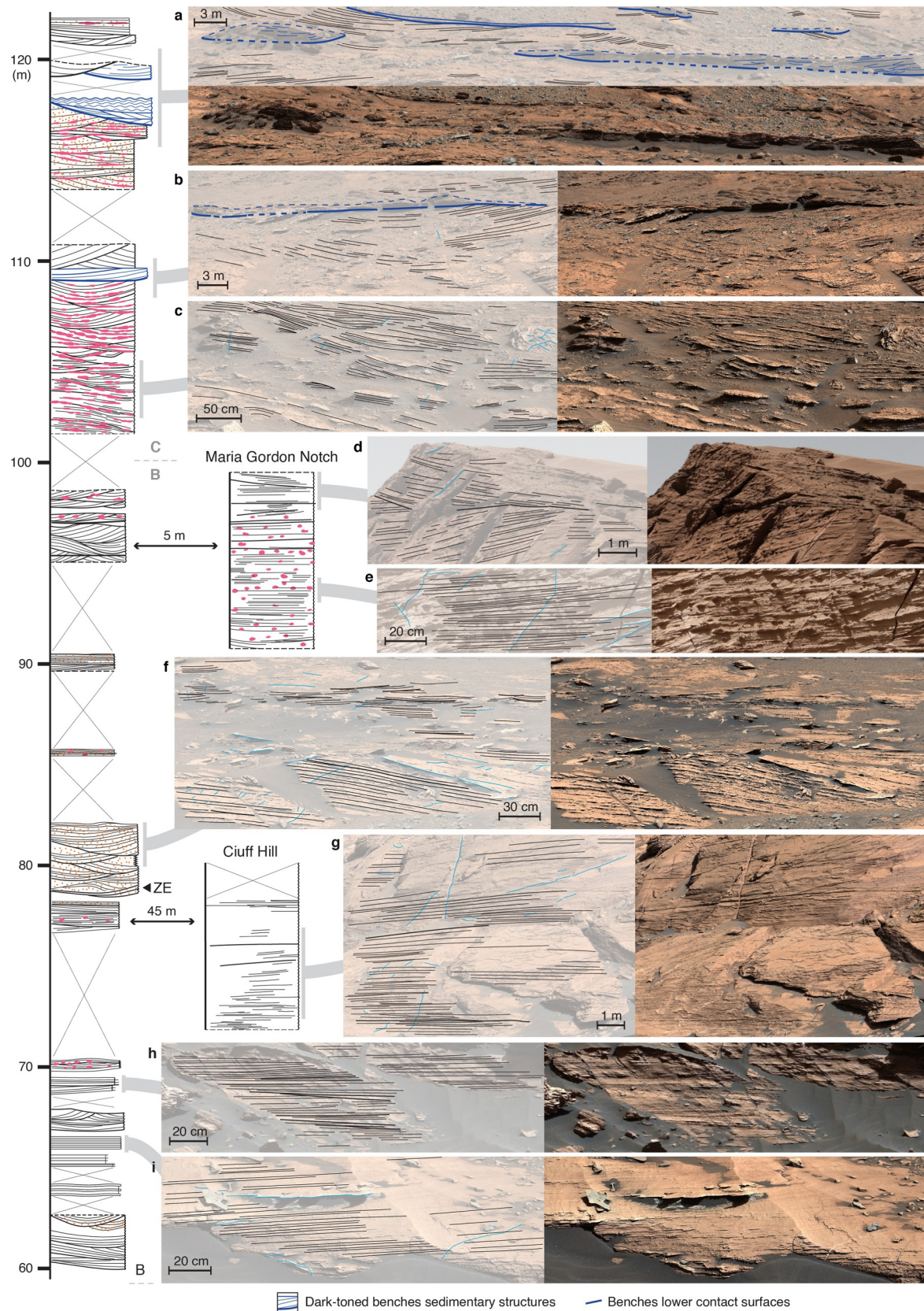


Figure 4.

3.1.4. Subordinate Depositional Structures

Other bedding types are observed locally. In interval C, the rover workspace indicates submeter scale trough cross-bedding with convex-up bedforms and lateral interruptions of bounding surfaces with sets (Figure 5f). These could be equivalent to complex assemblages observed in isolated patches between large cross-bedded sets seen at distance at equivalent elevation (Figures 8d, 8f, 9b, and 9c). Finally, near the top of interval D, meter scale tabular cross-bedding is inferred, although partially obscured by abundant nodular texture (Figure 6a). This type and scale of cross-bedding appears unique to interval D.

3.2. Nodular Textures, Distribution and Composition

A variety of nodule morphologies and internal textures are observed throughout the succession (Figure S1d–S1i in Supporting Information S1), including dendritic and crystal shapes (Figure 3h), sub-spherical (Figure 3a) as well as clustered lumpy textures (Figures 6a–6d). Importantly the density of nodules that crop out varies along the stratigraphy (Figure 10). This distribution of centimetric nodules based on workspace images is overall consistent with nodule densities measured using other methods (Seeger & Grotzinger, 2024). Interval B is notably devoid of dense nodular features, whereas all other intervals show high nodule densities. Meter-scale, vertical changes in nodule density are also observed (e.g., Figures 3a–3e). In interval C, dense nodular overprinting can occur below dark-toned lenses, which are themselves devoid of nodular textures (Figure 5j). In addition, the organization of nodules within host rock also varies, although most occurrences are locally spread uniformly, there are organized patterns such as polygonal (Figure 3g) or lineated (Figure 3f).

The composition of nodules is dominantly associated with combined sulfur and Ca and/or Mg cation enrichment relative to the host bedrock, which reflects the presence of calcium and magnesium sulfate compositions in the nodules (Figures 10a–10d, Figure S4 in Supporting Information S1). ChemCam targets document the composition of nodular lithologies with multiple analysis points (up to 5) and constrain the bulk composition for each nodule. Overall, nodule compositions are consistent with a mixture of sulfate-depleted host bedrock and sulfate end-members reaching up to 52 wt.% Ca-sulfate or 59 wt.% Mg-sulfate enrichment (Table S1 in Supporting Information S1). Sulfate minerals are also present in the smooth textured host bedrock, in particular in interval B, mostly in the form of Ca-sulfate enrichment (Figure 10b). The scattering of ChemCam point-to-point composition is indicative of heterogeneity at the hundred-micron scale. Whereas host bedrock depleted in sulfates show homogeneous compositions with points tightly clustered around 2.3 wt.% CaO and 4 wt.% MgO (Figure S3 in Supporting Information S1), sulfate enriched rocks show considerable heterogeneity in CaO and MgO contents. Overall, the variability of Ca-sulfate enrichment suggests they are a coarse-grained, yet relatively sparse component of the sedimentary matrix. Mg-sulfate enrichments, by contrast, are more grouped within 20–40 wt.% enrichment, indicative of a finer, more homogeneous intrasediment mineralization associated with the nodules. The most extreme Mg-sulfate enriched nodular bedrock is found near the Marker Band in interval D (Figure 10d). This location also corresponds to the highest water content, measured independently by the DAN instrument and therefore attributed to hydrated Mg-sulfate (Litvak et al., 2025). Within this area, the Canaima drill sample confirmed a significant abundance of hydrated Mg-sulfate both present as amorphous (19.4 wt.%) and as crystalline (starkeyite, 2.3 wt.%) components (Chipera et al., 2023). Other Mg-sulfate enrichments (20–40 wt.%) are found throughout intervals A, C and D, and associated with nodular textures. Sulfate enrichment is notably scarce within the dark-toned lenses of interval C (Figure S4 in Supporting Information S1). Point-to-point ChemCam data indicate Mg and Ca enrichments without associated sulfur, and with only a few sulfate detections (Figure 10c). Variability is consistent with a sandstone with compositions pointing to Mg and Ca-enriched silicate grains possibly olivines and low to high-Ca pyroxenes. There are also occurrences of sulfur enrichment without clear associated cations, potentially an indication of native sulfur enrichment.

3.3. Lithostratigraphic Succession

The stratigraphic column subdivision into 4 intervals (A to D) is defined on the basis of their general outcropping expression and the presence or absence of specific textural elements and associated chemical composition

Figure 4. Stratigraphic section from 60 to 125 m elevation. This interval transitions near elevation 100 m from smooth bedrock with planar bedding to subplanar crossbedding (interval B) into nodular crossbedding hosting dark-toned erosion resistant benches (interval C). Legend as in Figure 3. Includes drill sample ZE (Figure 2). Image identification: mcam101234 (a and b), mcam101213 (c), mcam101156 (d), mcam101120 (e), mcam100985 (f), mcam100916 (g), mcam100912 (h), mcam100910 (i). Credit: NASA/JPL-Caltech/MSSS.

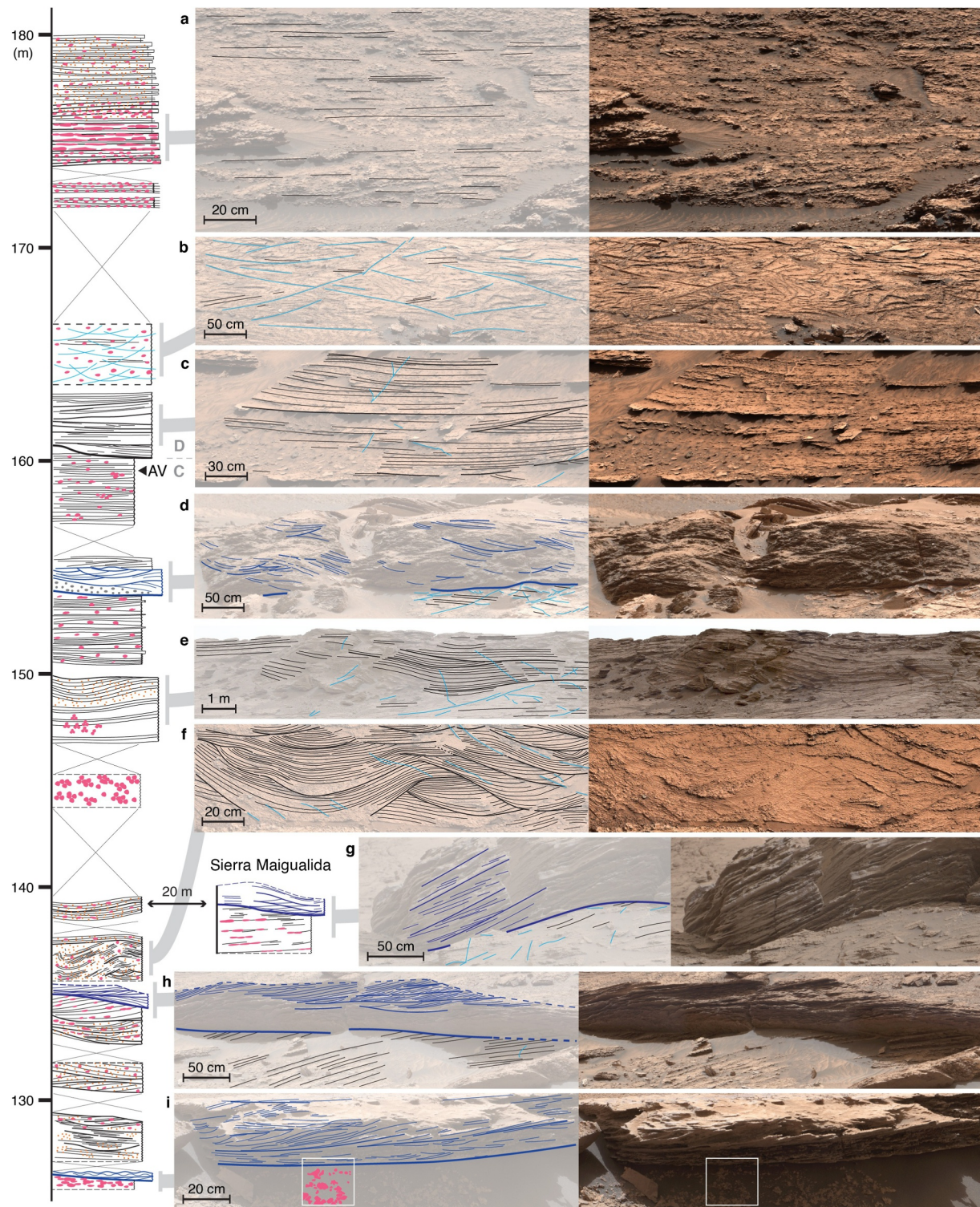


Figure 5. Stratigraphic section from 125 to 180 m elevation. This interval covers transition from large scale crossbedding with numerous dark-toned resistant horizon (interval C) into planar bedding (interval D), occurring at a sharp and irregular contact near elevation 160 m. Legend as in Figures 3 and 4. Includes drill sample AV (Figure 2). Image identification: mcam102402 (a), mcam102354 (b), mcam102265 (c), mcam102110 (d), mcam102074 (e), mcam102033 (f), mcam102048 (g), mcam101998 (h), mcam101986 (i). Credit: NASA/JPL- Caltech/MSSS.

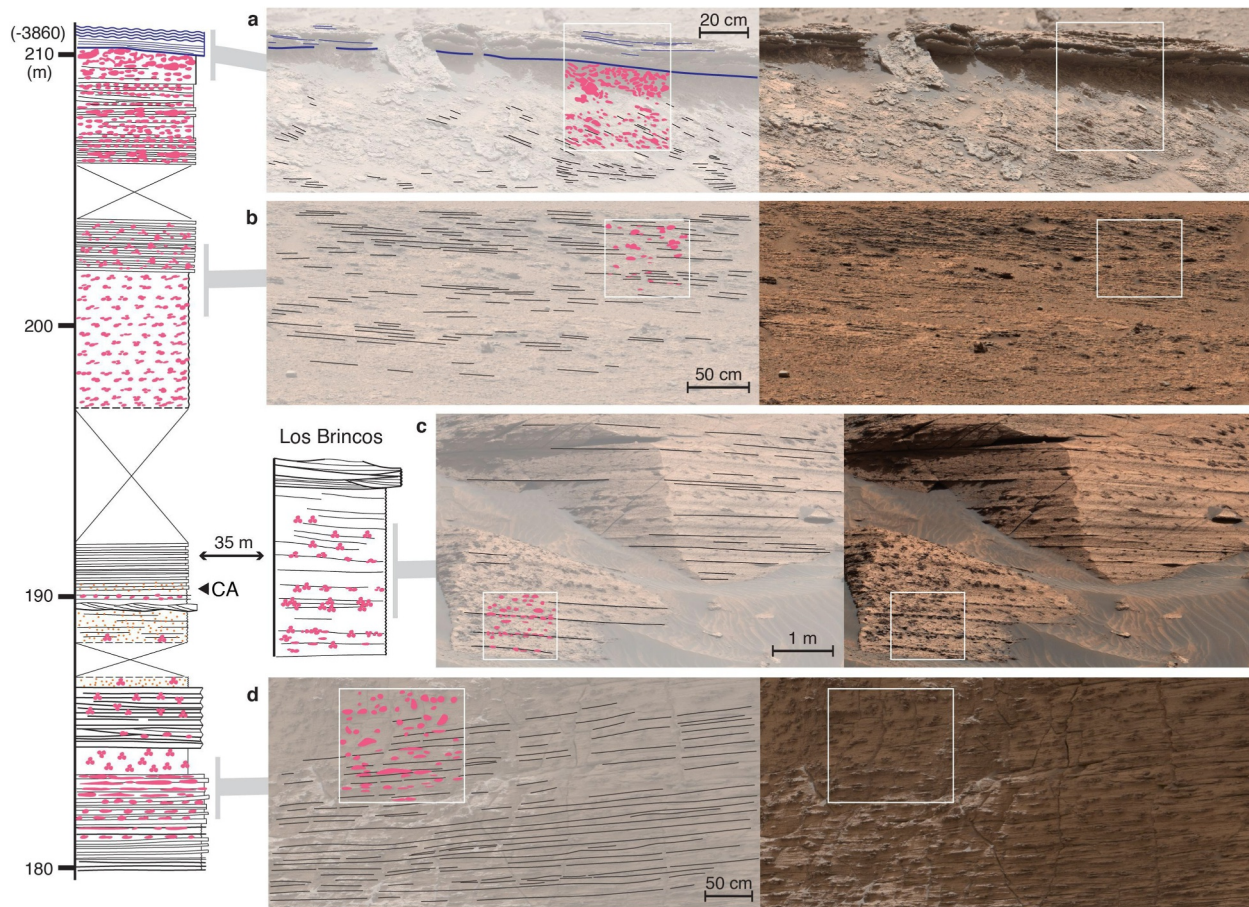


Figure 6. Stratigraphic section from 180 to 210 m elevation. This top section is dominated by planar strata overprinted by a variably dense nodular texture up to the base of the Amapari Marker Band erosion resistant outcrop (Mondro, Grotzinger, et al., 2025), marked by an alteration horizon and a sharp contact (Farrand et al., 2025). Legend as in Figures 3 and 4. Includes drill sample CA (Figure 2). Image identification: mcam103354 (a), mcam102968 (b), mcam102646 (c), mcam102486 (d). Credit: NASA/JPL- Caltech/MSSS.

(e.g., nodules) as summarized in Table 1. Across the explored 210 m of elevation, we delimited these 4 intervals as follow:

1. The lowermost interval (A) is primarily characterized by a distinct regional escarpment that is interpreted to mark a low-angle unconformity that separates stratal packages that both show a dense nodular texture (Meyer et al., 2024). Planar to subplanar primary stratification is only visible near the base of the section near 5 m elevation (Figure 3i). Above, 5–15 m below the scarp, diverse nodular textures are observed, including polygonal ridges (Figure 3g) or coalescent micro-nodules (Figure 3h). At the scarp itself, sedimentary structures are significantly obscured by dense nodular fabrics (Figure 3f). Upsection, decreasing nodule density allows for visibility of low angle cross-bedding near 35 m elevation (Figure 3e). Cross-bedding becomes prevalent up to 60 m of elevation with a variety of nodular textures (Figure 3a).
2. Interval (B) is marked by scarce nodular textures, and the continued prevalence of cross-bedding (Figures 4f and 4g), along with locally planar and subplanar bedding (Figures 4h and 4i). This interval is generally less well exposed, slightly recessive compared to other sections and so presumably less cemented, consistent with a lesser abundance of erosion resistant nodules.
3. Interval (C) starts near 100 m elevation with an abundance of centimeter-scale nodules that cluster along large-scale cross-bedding, enhancing laminations (Figure 4c). Its lower contact may also coincide with a bounding surface that is visible on the top of Maria Gordon Notch in the distance (Figure 4d). This interval notably encloses dark-toned sediment bodies (e.g., Figure 4a), lenticular or elongate, with irregular lower contacts, that occur scattered through nodule-bearing crossbedded strata up to 160 m elevation.

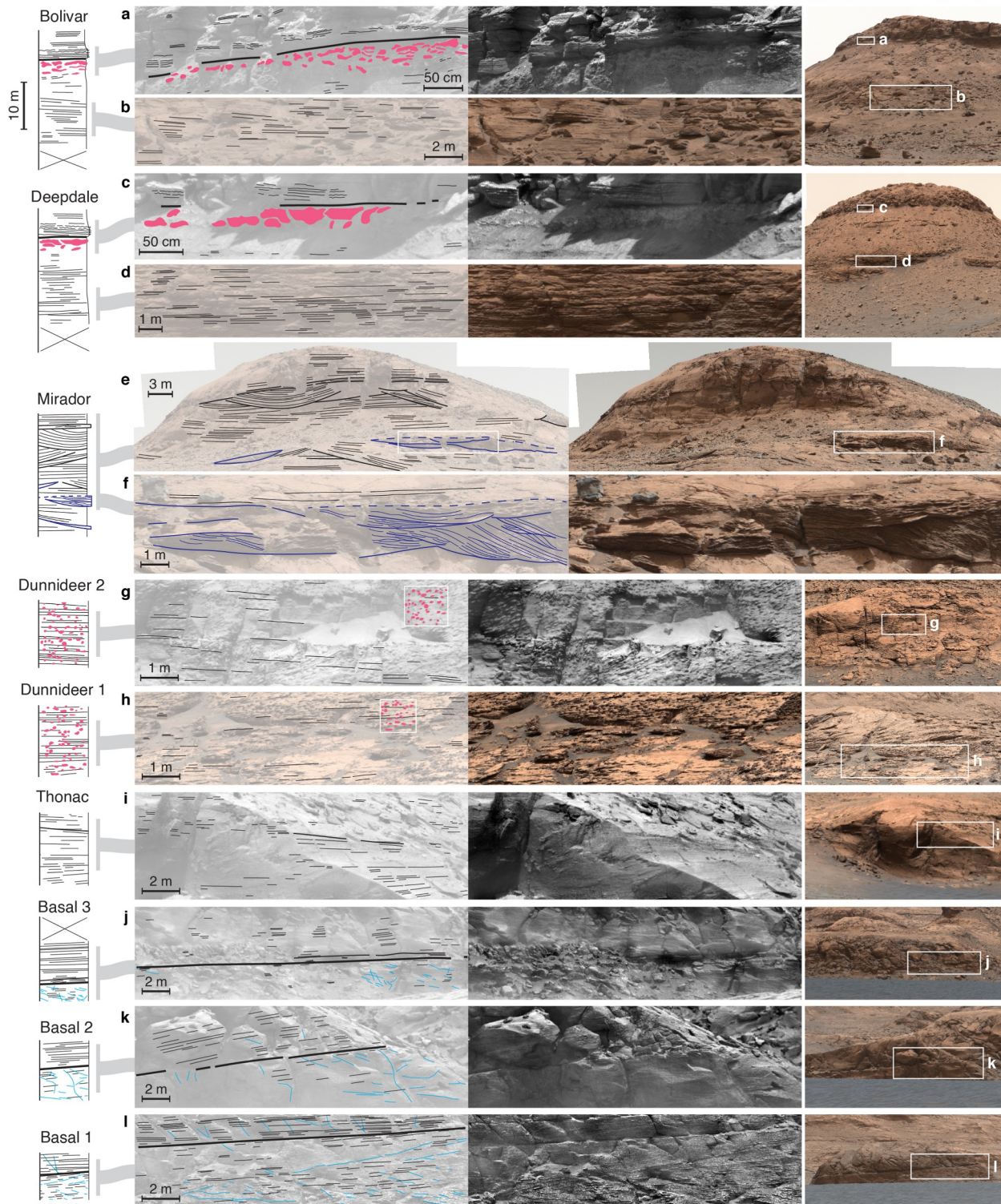


Figure 7. Stratigraphic sections from outcrops visible at long distance, up to 250 m away. This series corresponds to relatively small outcrops describing less than 30 m of stratal thickness. From left to right: stratigraphic column, image with tracing overlay, original image and/or context image. Legend as in Figures 3 and 4. Image identification: ccam02601 LD_Bolivar_3601 (a), mcam102130 (b), ccam03589 LD_Deepdale_3589a (c), mcam102905 (d), mcam101234 (e and f), ccam03153 LD_Sulfates_3153a (g), mcam100404 (h), ccam02122 LD_Thonac_3122 (i), ccam04962 LD_Sulfates_2962a (j), ccam06962 LD_Sulfates_2962c (k), ccam04989 LD_Sulfates_2989a (l). Panel (j) has been also reconstructed in 3D using stereo imaging (Caravaca et al., 2021). Image credit for MastCam: NASA/JPL-Caltech/MSSS/IRAP, ChemCam: NASA/JPL-Caltech/LANL/CNES/CNRS/IRAP/IAS/LPG.

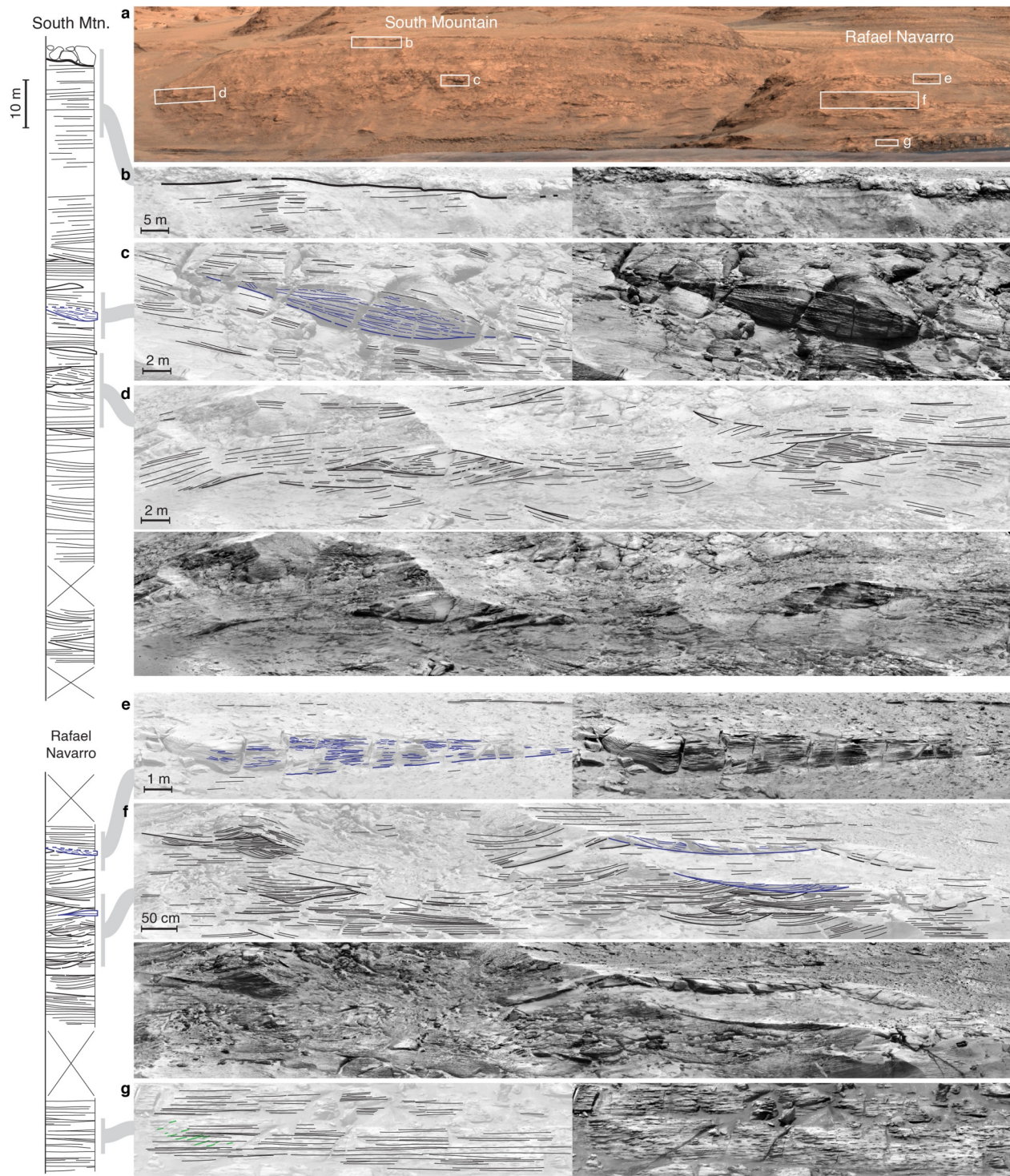


Figure 8. Stratigraphic sections from outcrops visible at long distance, from 300 to 600 m away. This series corresponds to kilometer wide and up to 100 m thick outcrops observed on buttes in the distance. From left to right: stratigraphic column, image with tracing overlay, original image and/or context image. Legend as in Figures 3 and 4. Image identification: mcam006060 (a), ccam02042 LD_Sulfates_3042a (b), ccam03151 (c), ccam01101 LD_Sulfates_3101b (d), ccam02245 LD_RN_3245 (e), ccam05962 LD_Sulfates_2962b (f), ccam02276 LD_RN_3276a (g). Panel (f) has been also reconstructed in 3D using stereo imaging (Caravaca et al., 2021). Image credit for MastCam: NASA/JPL-Caltech/MSSS/IRAP, ChemCam: NASA/JPL-Caltech/LANL/CNES/CNRS/IRAP/IAS/LPG.

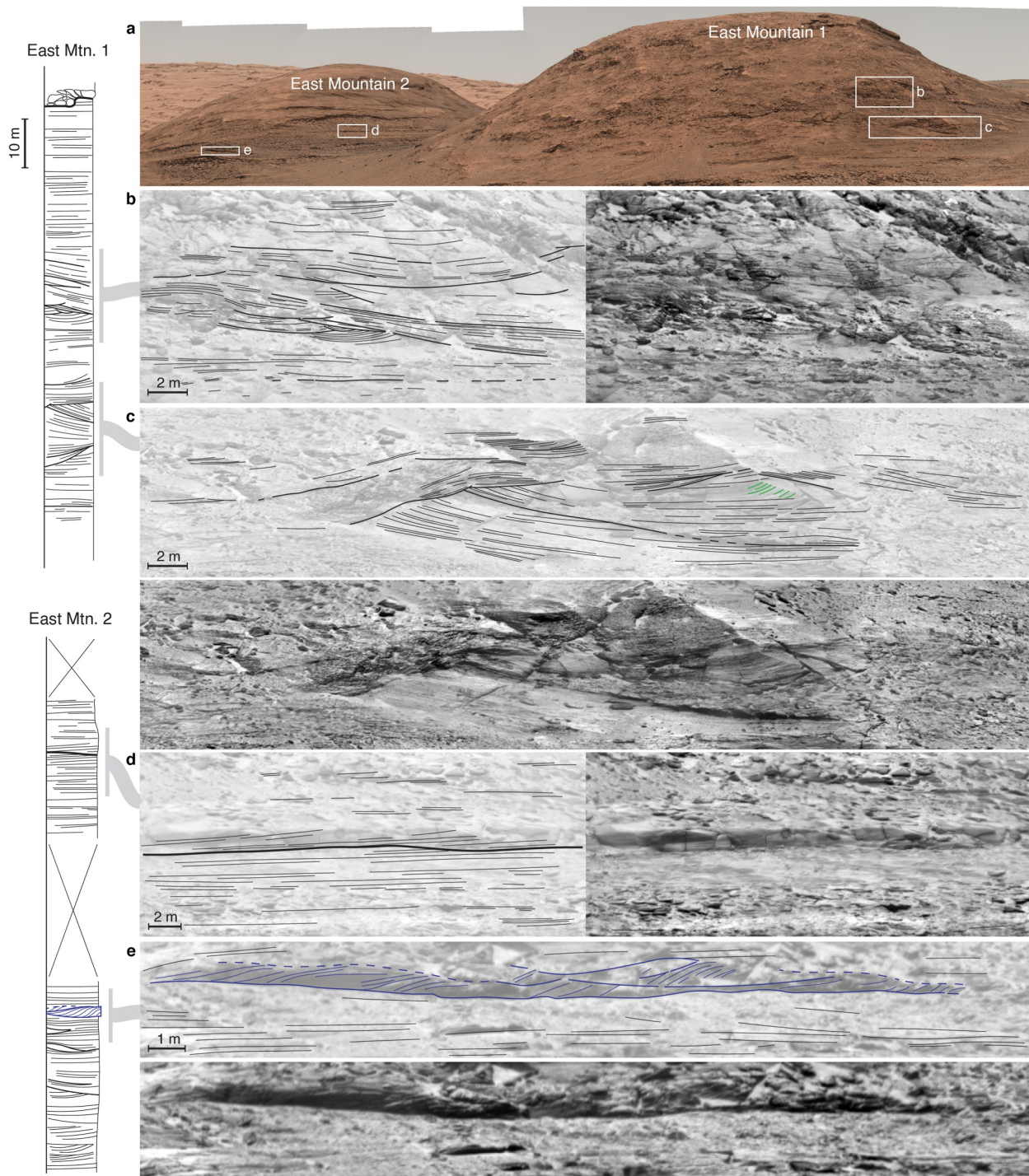


Figure 9. Stratigraphic sections from outcrops visible at long distance, from 0.5 to 1.5 km away. This series corresponds to relatively small outcrops describing less than 30 m of stratal thickness. From left to right: stratigraphic column, image with tracing overlay, original image and/or context image. Legend as in Figures 3 and 4. Image identification: mcam015887 (a), ccam02101 LD_Sulfates_3101a (b), ccam03047 LD_Sulfates_3047a (c), ccam04058 LD_Sulfates_3058b (d), ccam02108 LD_Sulfates_3108 (e). Image credit, MastCam: NASA/JPL-Caltech/MSSS/IRAP, ChemCam: NASA/JPL-Caltech/LANL/CNES/CNRS/IRAP/IAS/LPG.

4. The uppermost interval (D) starts above an irregular contact and shows various types of cross-stratification (Figure 5c), but higher up in the stratigraphy is dominantly characterized by planar to subplanar lamination (Figure 5a). Nodule density is variable and generally increases upsection (Figure 6). This interval is capped by the Amapari Marker Band (Figure 6a).

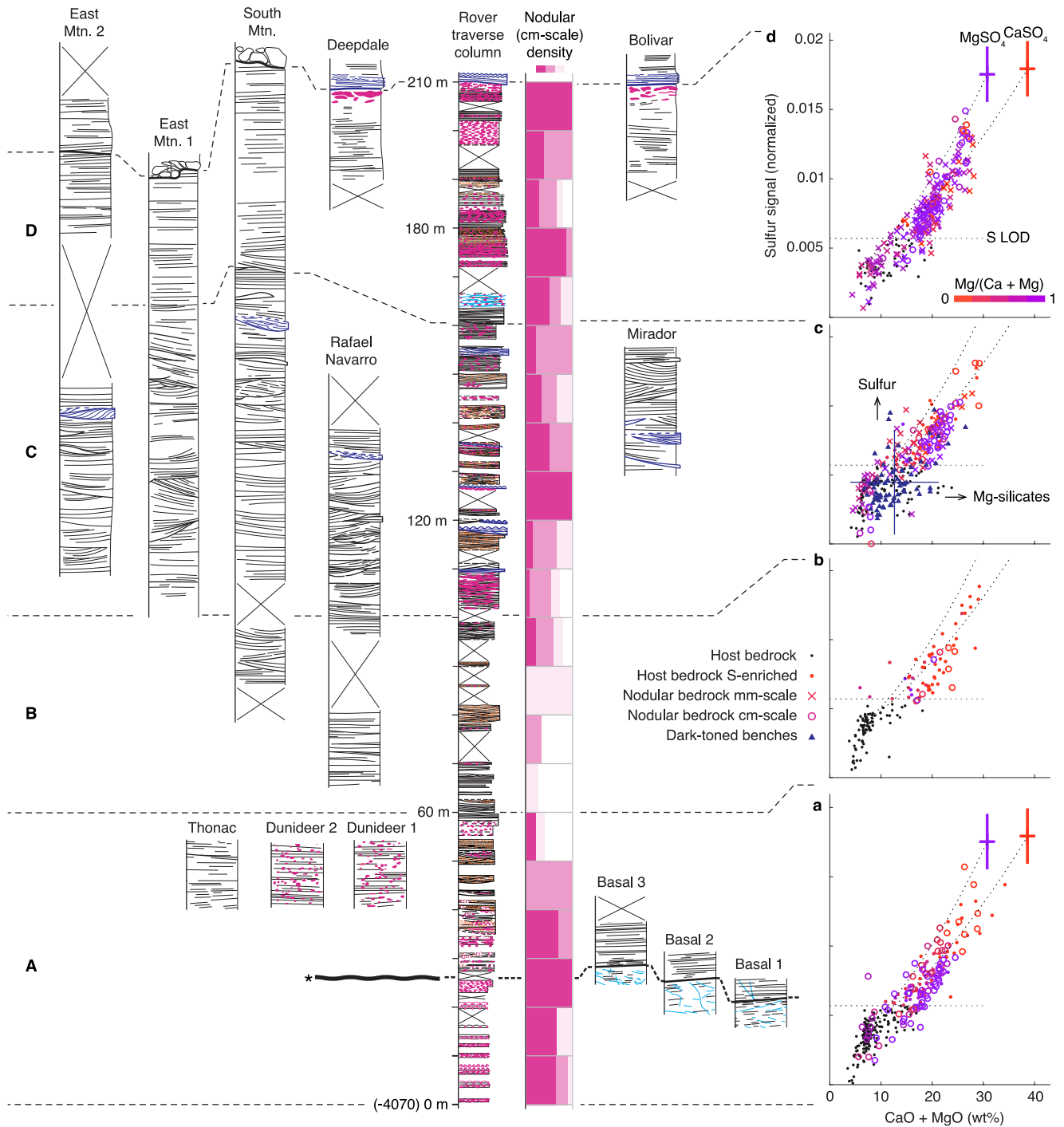


Figure 10. Overview of results in stratigraphic columns and all corresponding intervals observed using both short-range and long-range rover images. *Regional unconformable contact in interval A (Meyer et al., 2024). The density of nodules and nodular textures is represented in 10 m intervals with 4 shades of red indicating the relative fraction with the following densities: high, medium, low and absent. For each interval, the composition of bedrock features as measured by ChemCam point to point analyses is shown with sulfur signal as a function of CaO + MgO content (a–d). Horizontal dotted line represents the limit of detection on sulfur equivalent to 10.6 wt.% SO₃ (Rapin et al., 2019). Oblique dotted lines represent mixing of average host bedrock composition with pure Ca- and Mg-sulfate compositions, with end-member references in red and purple respectively.

Table 1
Summary of Major Sedimentary Structures and Nodular Textures Observed for Each Interval

Interval	Prevalent sedimentary structures	Nodular textures	Nodule density
D	Planar to subplanar bedding, low-angle crossed laminations	Lumpy, agglomerated into clusters, mm-scale granular	High to saturated
C	Large trough cross-bedding enclosing small-scale trough to tabular cross-bedding within lenticular bodies	Lumpy and agglomerated into clusters highlighting bedding, mm-scale granular	High (absent in lenses)
B	Large trough cross-bedding with occurrences of planar to subplanar	Concretionary, some mm-scale nodules	Low or absent
A	Planar to subplanar bedding, regional truncation and transition to large trough cross bedding	Dendritic, organized in lineated and polygonal patterns, lumpy and variably coalescent	High to saturated

4. Interpretation

Here we discuss the interpretation of the stratigraphic succession here by distinguishing possible depositional conditions, that is dry, damp or wet, according to sedimentary structures and other features of interdune deposits as defined by Kocurek (1981).

4.1. Depositional Environments

Large trough cross-bedding identified in intervals A, B and C is the main evidence for eolian deposition. The scale of these features, with troughs tens of meters long and set thicknesses up to 5 m, precludes a subaqueous origin in the interpreted setting. The corresponding tidal or fluvial flow needed, at least 6x dune height (Bradley & Venditti, 2017), of which only a small fraction is preserved within set thickness, is likely not suitable to the context of Gale crater's closed basin. The geometry of cross stratification is dominantly characterized by large trough surfaces indicating strongly three-dimensional dunes likely due to persistent unidirectional wind transport (McKee, 1979; Rubin, 2012). Variable set thicknesses up to 5 m could reflect fluctuation of climbing rates related to the sand budget in the eolian system, or differences in dune behavior from one dune to the next, considering their three-dimensionality. Sets of convex-up bedforms within these stratal packages, also likely of eolian origin due to their scale (Figure 8d), were observed at longer range (Rapin et al., 2021), and may represent the preservation of superimposed laterally shifting lee-side spurs common to eolian cross-strata and pointing to locally high accumulation rates. These convex-up bedforms combined with isolated sets of zig-zag like structures (Figure 8f) are thought to reflect high aggradation rate and reverse flow regimes (Rubin, 1987). In addition, trough cross-bedding exposed obliquely at low angle (e.g., Figure 5f) may present sets of laminae with both enhanced concave and convex shapes due to geometry of exposure.

It is noteworthy that there are no sand grains visible within the host bedrock matrix, precluding an assessment of grain size distribution, and indicating the bulk of the sediment is silt size or finer as defined by the resolution of the rover close up images (Meyer et al., 2024). A possible explanation for this is the local eolian reworking of composite particles of lacustrine mudstones as the dominant eolian sediment source in the succession (Li & Schieber, 2018; Schieber et al., 2026; Yawar et al., 2020). This scenario is consistent with the fact that host bedrock, which is typical of compositionally mature altered siliciclastics (Mangold et al., 2019), remained of similar chemical composition along the traverse throughout the stratigraphy into the intervals with large-scale cross-stratification (Meyer et al., 2024; O'Connell-Cooper et al., 2025). The basin-wide unconformity identified in interval A (Meyer et al., 2024), as an erosive surface into lacustrine sediment below, could have contributed as a major intrabasin eolian sediment source composed of mudstone particles. Furthermore, burial diagenesis of reworked sediment could have led to the alteration of original grain textures while also contributing to void filling and cementation, as previously reported in Gale crater (Edgett et al., 2020).

Dark-toned benches, which sporadically occur within interval C, show a number of features characteristic of subaqueous deposition, including (deca-)meter-scale lens-shaped bodies lying atop an erosive concave bottom contact, as well as cross-stratifications and laterally accreting, dipping, sigmoidal strata. These lenses are observed to interfinger and even be sealed by the regional aeolian-dominated bedrock. These geometries are in

line with short-lived (episodic), high energy cut and fill fluvial channels occurring in an interdune setting (Caravaca et al., 2025). This is further supported by the presence of symmetrical ripples at the top of several dark toned lenses, implying reduced depositional energy toward the end of the depositional episode. This is interpreted as probable abandonment of the channels and formation of isolated ponds or oxbow lakes in-between larger aeolian dunes (Caravaca et al., 2025; Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025). The presence of these lenses indicates a wet eolian depositional regime where dunes are formed by eolian transport with a shallow water table, locally above the sediment deposition surface. Rapid deposition rate of the lenses is consistent with fresh surface water injected from the rim and/or outside Gale crater into the basin instead of rise of the ground water in the dune field.

Planar to subplanar bedding, occurring in interval A and dominant in interval D, could indicate damp or intermittently wet interdune depositional environments. In the damp environment hypothesis, the subplanar bedding would represent large low-relief adhesion dunes within larger scale interdune flats, producing low-angle cross stratification (Kocurek, 1981). Alternatively, subplanar bedding may reflect subaqueous deposition, such as prodeltaic mud lobes similar to described in mudstone former strata (Schieber et al., 2024). While discrimination between the two interpretations is elusive from the lack of small-scale observables, they both indicate a high water table near or above the sediment surface.

Overall, the new analysis is consistent with the succession of depositional environments proposed by initial assessment of long distance (Rapin et al., 2021) and close range rover data (Meyer et al., 2024). It indicates fluctuating depositional environments, with an upward transition from wet to dry in interval A, with continuation of eolian deposition (Meyer et al., 2024; Rapin et al., 2021) until fluvial and lacustrine deposition reoccurs sporadically in interval C and at the Marker Band contact above interval D, indicative of a general rise of the water table (Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025; Rapin et al., 2021).

4.2. Timing of Sulfate Formation

Understanding the timing for the formation of sulfates in nodules and bedrock is crucial to deciphering its potential environmental implications. The absence of primary evaporite textures such as bottom growth crystals apparently suggests sulfate deposits are not syndepositional, and the formation scenarios proposed so far favor late-stage burial brine crystallization (Meyer et al., 2024; Seeger & Grotzinger, 2024). Yet, the origin of such brines forming late stage secondary evaporites has remained unidentified. In terrestrial settings, secondary evaporites are commonly adjacent to primary evaporitic strata and serve as a source for later stage subsurface brines (Warren, 2016). In addition, primary evaporites, such as bottom growth salt crystals, are accessory remnants in terrestrial evaporitic basins, limited to brine lake perimeters at times of supersaturation. These primary components are rarely preserved due to dissolution by freshening waters, or overprint by secondary evaporite formation during either early or late stage burial (Warren, 2016).

In addition, there are persistent concerns with regard to forming significant amounts of Mg-sulfate observed in the stratigraphy by late-stage, post-burial, brine circulation. First, the pore-filling volume required is limited by compaction and while some nodules are enriched with less than 20 wt.% sulfate (Table S1 in Supporting Information S1), a number of them are enriched near 50 wt.%, representing >50% per volume, a situation more plausible with poorly compacted sediments (Giles, 1997). Secondly, Mg-sulfate is an extremely soluble salt which requires extreme concentrations to trigger precipitation. Such low water activity precludes further concentration by alteration of silicates, and so these late-stage extremely soluble burial salts should be derived by dissolution of the same salts from a local source. Mg-sulfate minerals such as kieserite may precipitate at depth due to sediment heating above 60°C, reducing solubility (Steiger et al., 2011). Yet, Mg-sulfate is here frequently associated with intrasediment Ca-sulfate in close proximity or intimately mixed (Figure 10, Tables S1 and S2 in Supporting Information S1). Since Ca-sulfate is two orders of magnitude less soluble than Mg-sulfate, this assemblage could not crystallize from the same Mg-sulfate supersaturated brine at depth due to its depletion in calcium ions. Finally, and more importantly, the stratigraphic partitioning is not consistent with late-stage diagenesis, that is the vertical distribution of volume and nature of sulfate enrichments follows the stratigraphy, with the highest Mg-sulfate enriched nodule density within interval of damp or wet eolian depositional environments, interval A, C and D, whereas interval B, formed by the accumulation of dry eolian sediments, is nearly devoid of nodules (Figure 10). Enhanced grain sorting in eolian systems is expected to enhance permeability and porosity in the accumulating sediments when compared to wet surface environments wherein smaller

particles, and even clay, can considerably reduce porosity and permeability (Beard & Weyl, 1973; Cabalar & Akbulut, 2016; Kapui et al., 2018). Late-stage brine circulation should have been best developed in presumably the most porous intervals, such as interval B, yet it is interval B that shows the least abundance of diagenetic nodules (Figure 10b).

We propose instead that most intrasediment sulfate enrichment could have originated during early diagenesis. In this scenario, the capillary evaporation of ground and meteoric waters exposed subaerially within the shallow subsurface of a dominantly eolian sediment succession triggers the precipitation of sulfates (Figure 11). Evidence of ice-free surface water bodies within these intervals (Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025) indicates liquid water persisted at or near the surface and suggests evaporation was also taking place. Variable degrees of supersaturation, sediment porosity, water inputs and other factors may have led to the diversity of nodule textures and growth habits observed. In particular, near surface brines are frequently highly supersaturated during dry periods, potentially leading to enhanced nucleation and fast, sediment inclusive, nodular growth, whereas deeper in the subsurface less saturated brines would contribute sparser and slower nodule growth. This scenario, with variable salinity in the shallow subsurface, is consistent with the proximity and intimate mixtures of intrasediment Ca-sulfates and Mg-sulfates. Fluid circulation also occurred at depth, with post-lithification episodes confined to fractures clearly indicated by Ca-sulfate veins (Banham et al., 2025). Late stage burial circulation likely modified the distribution of salts, but would be limited to altering primary textures and enriching a few percent of Mg-sulfates, such as kieserite, in the host bedrock (Tutolo et al., 2025).

4.3. Stratigraphic Sequence

We interpret the succession with the following scenario, combining depositional environments and early diagenesis, periods of sediment accumulation interrupted by variably erosive hiatuses forming supersurfaces (Kocurek, 1988) (Figure 12), described in ascending stratigraphic order:

1. The lowermost interval A includes a major low-angle unconformity interpreted to result from a regional deflation surface that cuts into marginal lacustrine sediments (Meyer et al., 2024), forming a major supersurface in the succession (SS1). Possibly, the onset of aridity fed more sediment regionally into the eolian system leading to the migration of climbing dunes and deposition of large trough cross-beds on top of the deflation surface. Damp clay-bearing sediment below acted as a barrier to fluids and, with increased evaporation regionally, led to a trapped shallow subsurface brine, supersaturating and crystalizing Mg-sulfate nodules.
2. Dry eolian conditions persist in interval B with variable local accumulation rates, possibly related to fluctuations of sediment availability, forming trough cross-bedded structures as well as subplanar strata. In this setting, the depositional surface was significantly higher above the saline water table, limiting evaporation and nodule growth.
3. In interval C the dry eolian system continues to accumulate large scale trough cross-bedded units, but is interbedded with deposits of recurrent fluvial flooding episodes (Caravaca et al., 2025). At the base of this interval the water table catching up with the sediment surface may have resulted in a bypass supersurface (SS2), a hiatus in deposition with minimal to no erosion possibly materialized by the contact near 100 m elevation (Figure 4d). These fluvial inputs carry relatively unaltered basaltic material (O'Connell-Cooper et al., 2025), with evidence of coarse Mg-silicate grains (Figure 10c). The fresh basaltic sand bodies were cemented early, likely by silica and Fe-oxides from partial dissolution of ferromagnesian silicates by less saline possibly more acidic surface waters, and buried as dark-toned lenses. Water table rising fed by both regional groundwater, snowmelt and/or meteoric water promoted evaporation of subsurface brines in the dune field and led to Mg-sulfate nodule growth in the host eolian sediment.
4. In the uppermost interval D, continued rise of the water table and limited eolian sediment supply was followed by slowly aggrading bedforms of a damp or wet environment. This change in sediment supply possibly resulted in a deflation and a supersurface (SS3) at elevation 160 m also described as an erosional surface by Roberts et al. (2026). With a water table near or at the surface, evaporation feeds the subsurface brine, leading to recurrent supersaturation and the formation of abundant intrasediment nodules. The eolian system then evolves into a deflationary regime due the onset of a drier climate and exhaustion of sediment supply, which cuts into the sediment down to the water table. This ultimately forms the lower contact of the Marker Band (Farrand et al., 2025), the second major supersurface (SS4) of the succession mapped regionally (Weitz et al., 2022). During deflation, the relative rise of the water table further enhanced evaporation and the

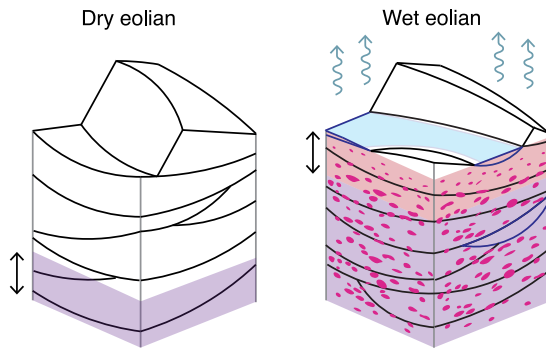


Figure 11. Nodule formation in early diagenesis. Saline groundwater (violet) fluctuates at different depths in dry and wet eolian settings (black arrow). Fluctuation near the surface (pale red) favors evaporation (blue arrows) through the vadose zone, saturation of brines and growth of Mg-sulfate nodules (red).

crystallization of nodules yielding the most elevated sulfate enrichment right below the contact (Figures 10d and 12, Table S1 in Supporting Information S1) (Litvak et al., 2025). Continued rise of the water table then leads to the deposition of the Marker Band lacustrine strata (Mondro, Fedo, et al., 2025; Mondro, Grotzinger, et al., 2025).

It is noteworthy that the stratigraphy as a whole mimics the evolution known in terrestrial wet eolian sequences subject to climate forcings (Gross et al., 2023; Havholm & Kocurek, 1994; Hème de Lacotte & Mountney, 2022; Mountney & Thompson, 2002). In this scenario, the evolution of the water table and sediment budget are locally linked by regional processes where the onset of drier periods released sediment for eolian transport, and wetter periods instead reduced availability of eolian sediment. These regional changes are presumably driven by larger scale climate forcings. Although a notable difference to Earth is the lower atmospheric density on Hesperian Mars (Slipski & Jakosky, 2016), which may have generated specific eolian structures such as wind-drag ripples (Lapotre et al., 2016), the basin-scale dynamics of dune fields is similar, suggesting stratigraphic records should be

similar (Ewing et al., 2017). Following the analogy, the activation of eolian sediment sources until exhaustion of supply, and climate fluctuations would have both primarily controlled the observed depositional sequence. This sequence of deposition and groundwater fluctuations also matches with hydrological models predicting either wet or dry depositional environments in Gale depending on climate forcings and infilling of the crater (Horvath & Andrews-Hanna, 2021). Basin-wide models indeed predict that both groundwater seepage and surface runoff likely both contributed significantly to Gale crater water input and controlled surface environments (Horvath & Andrews-Hanna, 2017).

In this sequence, the absence of clay minerals in the bedrock (Rampe et al., 2023), which contrasts with the strata below the unconformity, and could be either due to a lower abundance of clays from the eolian sediment sources or the extreme salinity of ground water during burial. It was proposed as a plausible mechanism to explain

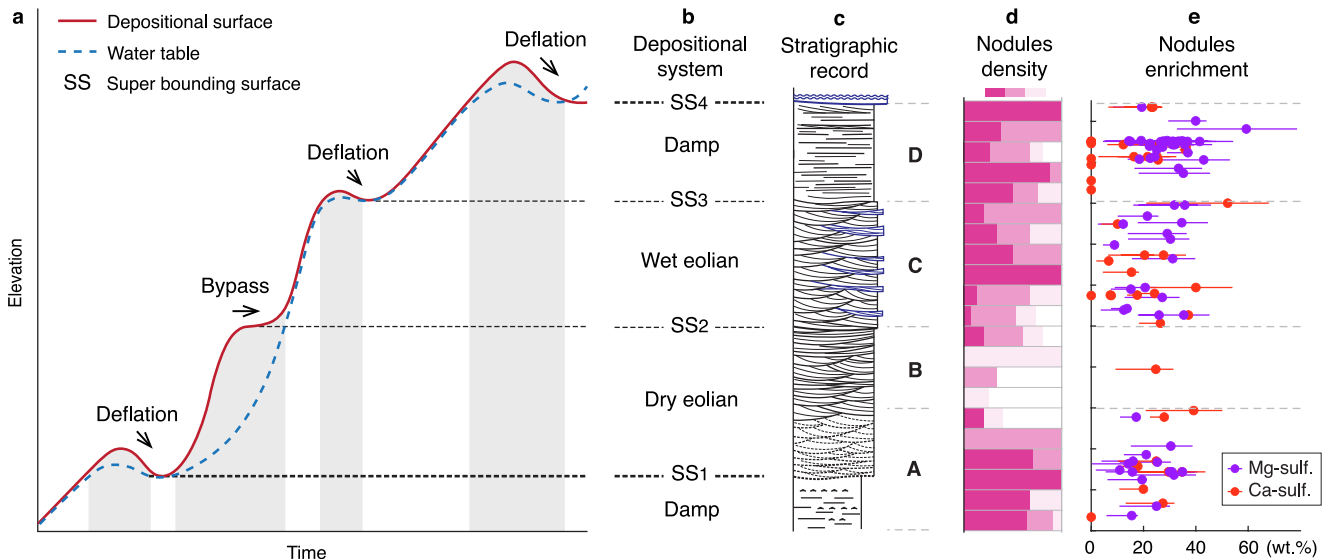


Figure 12. Tentative interpretation of water table and sediment surface fluctuations corresponding to the stratigraphic record. Evolution of depositional surface following water table forming deflation or bypass surfaces at the stratigraphic levels of supersurfaces (SS1 to SS4) observed regionally (thick dashed line) or only identified locally (thin dashed line), diagram modified after Mountney and Thompson (2002) (a). Interpreted dry periods (highlighted in grey) are mostly removed from the stratigraphic record due to deflations. Summary of interpreted depositional system (b) and corresponding synthetic stratigraphic column (c). Density of nodules and nodular textures observed on exposed bedrock along the rover traverse (d), same as Figure 10. Sulfate enrichment in nodules analyzed by ChemCam, with average content for each nodule presented as either Ca- or Mg-sulfate enriched depending on the most abundant cation (Table S1 in Supporting Information S1); horizontal error bars represent the uncertainty on inferred average sulfate content (e).

alteration patterns of the underlying unit at the Vera Rubin ridge, where a mineralogical assemblage enriched in hematite and depleted in clays is observed laterally equivalent to clay-rich strata (Bristow et al., 2021). This scenario is consistent with our proposed sequence as the Mg-sulfate saturated brine, which would be forming immediately above the unconformity due to evaporation (Figure 11), could seep downward due to its higher density. Therefore, the clay-sulfate transition as identified from orbit would be the result of a change in both depositional environment and diagenesis. The patchy occurrence of sulfate absorptions observed in the stratigraphy from orbit (Fraeman et al., 2016; Sheppard et al., 2021) may reflect variable degrees of salinity-driven destruction of clays, or lower clay abundances in the sediment source. Instead of clays, recent observations immediately above the transition interval reveal the association of Fe-carbonate with Mg-sulfates interpreted as early diagenetic (Tutolo et al., 2025). This new assemblage, likely formed following eolian deposition (Roberts et al., 2025), is consistent with a continuation of evaporitic settings and highlights that the precipitation of carbonates may have been either inhibited or favored due to subtle hydrological controls (Loche et al., 2024). The evaporative formation mechanism is also corroborated by the isotopic composition of these Fe-carbonates (siderite and ankerite) identified in drill samples within and adjacent to the sequence. Fe-carbonates found at the top of the clay-bearing unit (Mary Anning), the base of the clay-sulfate transition (Bardou), and above the transition (Tapo Caparo and Ubajara) all feature extremely elevated $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, which have been linked to repeated wet-dry cycling (Burt et al., 2024).

5. Discussion on the Origin of Sulfur

On Earth, continental brines most commonly form by recycling of evaporites exposed in the catchment of hydrologic systems (Warren, 2016). On Mars at Gale crater, there are no obvious exposures of hydrated sulfates in the catchment of Gale crater basin according to orbital data (Buz et al., 2017; Ehlmann & Buz, 2015; Sheppard et al., 2021). It does not, however, rule out the possibility of recycling dissolved sulfates and other ions by groundwater elsewhere and delivered to the basin. Similarly to what has been proposed for the Burns formation in Meridiani Planum (McLennan et al., 2005), sulfate observed in our interval may also have resulted from intra-basin eolian reworking of surface evaporite minerals and their dissolution before forming nodules in the water table fluctuation zone (Figure 11), which ultimately preserved them in the stratigraphy.

Sources other than recycling can contribute to the salinity of surface and near surface water, in particular the weathering of magmatic rocks by acidic fluids can produce sulfate rich brines (Tosca & McLennan, 2006). In this scenario SO_2 emitted by volcanoes forms sulfuric acid with water either in the atmosphere as aerosols or at the surface. Such volcanic origin for sulfate in Gale crater is in line with expected magmatic activity and degassing in the early Hesperian (Baratoux et al., 2013; Gaillard et al., 2013). Importantly, in the Mt. Sharp group bedrock, detrital components indicate chemical alteration of mafic minerals consistent with open system weathering (Bristow et al., 2018; Dehouck et al., 2022; Mangold et al., 2019). In Gale's closed-basin hydrology, leached ions would accumulate in ground waters and gradually evaporate to create sulfate-rich brines. In addition, fluvial deposits identified in interval C in the form of the dark-toned sandstone lenses correspond to the least altered sediments of basaltic composition (O'Connell-Cooper et al., 2025), and interestingly present tantalizing hints of sand-sized native sulfur (Figure 10c). These detections would be consistent with sulfur-rich volcanism that can produce significant SO_2 as well as native sulfur S_8 deposits (Bellino & Sun, 2025).

6. Conclusions

Our detailed stratigraphic documentation of the transition interval from clay to the sulfate-bearing units reveals a history of environmental change and diagenesis, offering new perspectives for understanding the fate of sulfur and potential high frequency climate cycles on Hesperian Mars. By integrating ChemCam data with sedimentary structures observable across scales, we highlight that the dominant sulfate enrichments are hosted within nodular textures found in specific intervals, a component overlooked by analyses limited to smooth host bedrock.

We propose an early diagenetic model where intrasediment sulfate nodules formed through capillary evaporation in the vadose zone at variable depth, in a damp or wet eolian system. This is supported by the stratigraphic partitioning of nodules, their elevated sulfate content requiring poorly compacted sediment, and their absence in the driest interval (B) and close association with intervals formed with water table at or near the surface (A, C, D). Later stage, burial-related processes may have also contributed to the formation or alteration of sulfates but cannot account for the observed partitioning of evaporites.

In this scenario, the succession represents a basin wide subaerially exposed evaporative system within a variably wet eolian environment gradually forming a hundred meters thick deposit. It is distinct from the extremely acidic fluids that formed sulfates in the Burns formation of Meridiani Planum given the absence of jarosite. The overall sequence, including aridification events, an eolian system punctuated by wet episodes, and finally a rising water table, indicates a fluctuating Hesperian climate recorded in Gale crater that is far more variable than a single, monotonous drying event.

We suggest that the fluctuating water table, likely driven by climate forcings, did not directly drive accumulation but placed a limit on deflations, thereby controlling the preservation of the stratigraphy. Our findings overall support a model for the intrabasin sequestration of sulfur on Hesperian Mars where early diagenetic evaporation concentrated salts within specific strata that are associated with wet intervals driven by climate forcings.

Conflict of Interest

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

Availability Statement

All geochemical data used in this paper are available via the NASA Planetary Data System (<https://pds-geosciences.wustl.edu/missions/msl/index.htm>). Sulfur LIBS signal acquired by the ChemCam instrument and calibration for sulfate abundance with associated uncertainties for each target with point-by-point classification used in this study is provided in attachment as supporting information (Tables S1 and S2 in Supporting Information S1) and can be found at <https://doi.org/10.5281/zenodo.22657652>.

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