Sedimentological and geochemical perspectives on a marginal lake environment recorded in the Hartmann’s Valley and Karasburg members of the Murray formation, Gale crater, Mars

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Key Points:

- Subaerial and subaqueous facies were identified within stratigraphy of the Hartmann’s Valley and Karasburg members of the Murray formation.
- Sedimentologic, stratigraphic, and geochemical evidence suggests that facies formed in a landscape capable of sustaining water.
- These members extend the range of facies and environments identified within the Murray formation.
Abstract

This study utilizes instruments from the Curiosity rover payload to develop an integrated paleoenvironmental and compositional reconstruction for the 65-m thick interval of stratigraphy comprising the Hartmann’s Valley and Karasburg members of the Murray formation, Gale crater, Mars. The stratigraphy consists of cross-stratified sandstone (Facies 1), planar-laminated sandstone (Facies 2), and planar-laminated mudstone (Facies 3). Facies 1 is composed of sandstone showing truncated sets of concave-curvilinear laminae stacked into cosets. Sets are estimated to be meter- to sub-meter-scale, consistent with low-height dunes. Thin stratigraphic intervals of Facies 1 and stacking patterns with Facies 2 and 3 support a wet aeolian dune interpretation. Meter-thick packages of planar-laminated sandstone (Facies 2) are interpreted to represent interfingering dune-interdune strata. Facies 3 consists of meter-thick packages of planar-laminated mudstone interpreted to represent lacustrine deposition with persistent standing water. Integration of geochemistry with each facies reveals some compositional control based on depositional process. Models for source rock composition from Alpha Particle X-Ray Spectrometer measurements show that facies derived from a basaltic source. Alteration indices and geochemical trends provide evidence that moderate chemical weathering occurred before compositional changes due to diagenesis. Differences of wt% FeO(T) and TiO₂ between facies are minimal, though trends between facies point to sediment sorting in transport. Comparisons to terrestrial basaltic sedimentary systems indicate that the Hartmann’s Valley and Karasburg facies reflect deposition in an environment where diverse subaqueous and subaerial facies persisted adjacent to a long-lived body of water.
Plain language summary

This study utilizes instruments from the Curiosity rover payload to study the facies and geochemistry of an interval of sedimentary rocks exposed at Gale crater on Mars. The Hartmann’s Valley and Karasburg members, the focus of this study, contain sedimentary facies that represent ancient lake and lake-margin environments. Lake deposits are consistent with deposition in standing water. Lake-margin deposits are consistent with wet subaerial dune and interdune formation. Models indicate that sediments for all facies were derived from a similar source composition. Geochemical trends indicate that sediment composition changed via chemical weathering. Slight compositional trends that correlate with relative grain size signatures suggest that sediment may have been sorted in transport. Facies and geochemistry collectively indicate that the depositional environments of the Hartmann’s Valley and Karasburg members persisted in a climate capable of sustaining standing water within lakes and along lake margins.

1. Introduction

Sedimentary successions, which are ubiquitous across Mars, have become prime mission targets in the search for understanding paleoenvironments including those potentially suitable for supporting life (e.g. Fairén et al., 2010; Grotzinger et al., 2014; Hurowitz et al., 2017; Malin & Edgett, 2000). Decades of Mars exploration have produced datasets with increasing coverage and resolution, which continue to refine interpretations of water-generated features represented in geomorphologic, stratigraphic, and compositional records across the planet.

Rover-based evidence for ancient lacustrine (e.g., Edgar et al., 2020; Grotzinger et al., 2015; Stack et al., 2019), aeolian (e.g. Banham et al., 2018; Grotzinger et al., 2005), and fluvial (e.g. Edgar et al., 2017; Williams et al., 2013) environments is abundant within the explored
sedimentary successions. Interpretations of stratigraphy from landscape- to grain-scales correlate with compositional records from orbital spectroscopy datasets that show distinct intervals of clay-, sulfate-, and Fe-oxide-dominated strata (Christensen et al., 2000; Fraeman et al., 2020; Milliken et al., 2010), supporting hypotheses that aqueous activity was widespread and dynamic through time.

Gale crater (5°S, 138°E), a 155 km diameter complex crater located along the dichotomy boundary just south of the equator, was the destination for the Mars Science Laboratory (MSL) Curiosity rover mission (Figure 1). The crater formed ~3.7 Ga (Le Deit et al., 2013; Thomson et al., 2011) and is filled by a younger succession of Hesperian (~3.6 Ga) strata, which is now exposed as a central mound. This stratigraphic succession represents an ideal location to study depositional environments and compositional signatures due to the continuous stratigraphy exposed in the 5.5 km-high central mound (Figure 1a; Aeolis Mons, informally Mount Sharp; Grotzinger & Milliken, 2012), which encompasses the globally documented transitions from clay- to sulfate- to Fe-oxide enriched bedrock (Bibring et al. 2006; Milliken et al., 2010).

The facies (Edgar et al., 2020; Fedo et al., 2018; Grotzinger et al., 2015; Stack et al., 2019) and geochemistry (Hurowitz et al., 2017; Mangold et al., 2019; Siebach et al., 2017) of the ~300 m thick Murray formation (Figure 1c), are consistent with lacustrine (and lacustrine-margin) environments that experienced long durations of standing water capable of generating hundreds of meters of preserved sediment. Bedrock geochemical and mineralogical signatures provide compositional constraints regarding basaltic source rocks (Bedford et al., 2019; Siebach et al., 2017) and the extent of chemical weathering (Frydenvang et al., 2020; Mangold et al., 2019), and diagenesis (Achilles et al., 2020; Bristow et al., 2021; Kronyak et al., 2019; Sun et al., 2019). In this context, the Hartmann’s Valley and Karasburg stratigraphic members of the
Murray formation remain described and interpreted at a cursory level, which precludes a full understanding of paleoenvironments and compositional evolution. A significant change in depositional processes and paleoenvironments is preserved in these two members as they record the first transition in the Murray formation stratigraphy from laminated mudstone to meter-scale cross-stratified sandstone. Development of a depositional model for the Hartmann’s Valley and Karasburg stratigraphic successions will ultimately contribute to ongoing investigations of habitable environments at Gale crater and their evolution through time.

Linked to unraveling basin evolution are the numerous chemical and physical processes that occur along the source-to-burial pathway that defines a sedimentary cycle (e.g. weathering, transport, diagenesis; Johnsson, 1993). Physical processes build sedimentary structures that group into sedimentary facies based on the depositional environment. The physical processes transporting sediment to the depositional environment drive hydrodynamic sorting that can cause changes in mineralogical proportions, and thus composition, from the original source composition by segregating grains based on density, size, and shape (e.g. Fedo et al., 2015; Mangold et al., 2011; McGlynn et al., 2012; Nesbitt & Young, 1996; Siebach et al., 2017). The interrelationship between depositional process, environment, and composition emphasizes the importance of simultaneous assessment of sedimentary textures and depositional processes as a framework from which to interpret composition. It is therefore critical to interpret bulk sediment composition in the context of facies and depositional environments within a sedimentary succession. Accordingly, this study builds an integrated depositional and compositional picture of the Hartmann’s Valley and Karasburg members of the Murray formation.

The main objectives of this study are to characterize the facies and interpret the paleoenvironments of the Hartmann’s Valley and Karasburg members of the Murray formation.
(Figure 1) and use the associated internal depositional processes to help frame the geochemical composition of both units. Specific objectives of this study are to: (i) identify sedimentary facies and assess variability and patterns, (ii) interpret associated depositional environments, (iii) assess the geochemistry to develop an understanding of source rock composition, chemical weathering, sediment transport, and diagenesis within the context of the interpreted facies and environments, and (iv) discuss implications for the evolution of the depositional systems at Gale crater.

2. Geologic, stratigraphic, and compositional context

2.1 Gale crater

More than 500 m of strata have been documented along the Curiosity rover traverse to date. The strata are subdivided into three groups (Figure 1b): (1) the Bradbury group, which comprises the intracrater plains (Aeolis Palus) and interfingers with the Mount Sharp group (Grotzinger et al., 2015; Williams et al., 2013), (2) the Mount Sharp group, which consists of the exposed Murray and Carolyn Shoemaker formation strata of the central mound (Bennett et al., 2022; Grotzinger et al., 2015), and (3) the Siccar Point group, which unconformably overlies the Mount Sharp strata (Banham et al., 2018, 2021). Basaltic sand deposits mantle the bedrock that comprises Mount Sharp (Figure 1b) and consist of a variety of active aeolian bedforms, including the dunes and ripples of the Bagnold dune field (Lapôtre & Rampe, 2018). The contrast between the northward slope of the landscape in the area of the crater explored by Curiosity and the near-horizontal orientation of the strata indicates that the crater basin was once filled with sediment and that the present-day landscape formed principally from erosion from aeolian activity (Grotzinger et al., 2015). Additionally, the negligible dip of the strata (Stein et al., 2020) has enabled elevation to be used as a proxy for stratigraphic height in the creation of a
working stratigraphic column for the mission (Figure 1c; Edgar et al., 2020; Stack et al., 2019), but many are interpreted from one main transect (e.g. Stack et al., 2019).

### 2.2 Murray formation

#### 2.2.1 Stratigraphy and composition

The Murray formation is subdivided into seven stratigraphic members based primarily on lithology (Figure 1c). Of the seven members, thorough facies analyses have been done throughout the Pahrump Hills (Grotzinger et al., 2015; Stack et al., 2019), Blunts Point, Pettgrove Point, and Jura members (Caravaca et al., 2022; Edgar et al., 2020), while more localized studies have been done throughout the Sutton Island member (Rapin et al., 2019; Stein et al., 2018). Much of the Murray formation consists of meters thick intervals of planar laminated mudstone that are interpreted to represent deposition in low-energy lacustrine basin environments (e.g. Edgar et al., 2020; Stack et al., 2019). More isolated outcrops of cross-stratified sandstone represent higher-energy deposition along marginal lacustrine settings (Fedo et al., 2018; Stack et al., 2019).

Whole-rock geochemistry and mineralogy throughout most of the Murray formation is consistent with dominantly basaltic sources (Rampe et al., 2020; Thompson et al., 2020). Subalkaline igneous compositions have been proposed as a primary source composition for the majority of the stratigraphy, with the exception of a localized silica-rich interval in the Pahrump Hills member which is thought to reflect derivation from a more evolved volcanic composition (Bedford et al., 2019; Berger et al., 2020; Morris et al., 2016; Siebach et al., 2017). Interpretations of geochemical trends attribute elemental enrichment and depletion to modification from weathering and diagenesis (Frydenvang et al., 2020; Mangold et al., 2019;
Analyses of drilled samples by the Chemistry and Mineralogy (CheMin) instrument show shifts in the relative amounts and compositions of primary and secondary minerals and amorphous phases throughout the stratigraphy which corroborate hypotheses of weathering and diagenesis under variable aqueous conditions (Achilles et al., 2020; Bristow et al., 2018; Rampe et al., 2020).

3. Methods

3.1 Sedimentology and stratigraphy

3.1.1 Rover traverse

Stratigraphic and geochemical observations of the Hartmann’s Valley member (HVm) and Karasburg member (Km) were made using data acquired along a ~2.7 km rover traverse across variable topography (Figures 1b & 2). Strata of the lower 18 m of the HVm were evaluated from multiple traverses of the same elevation range, enabling assessment of lateral facies variability (Figure 2). The traverse across the upper part of the HVm and the entirety of the Km was a monotonic ascent that precluded an assessment of lateral continuity. Therefore, the profile in Figure 2 subsequently leaves interpretations of the subsurface distribution of strata along the second portion of the traverse blank.

3.1.2 Instruments

Sedimentological and stratigraphic observations were conducted using images taken with a suite of cameras on the rover mast and arm. Images of bedrock taken with the Navigation Camera (Navcam; Maki et al., 2012), Mast Camera (Mastcam; Malin et al., 2017), Mars Hand Lens Imager (MAHLI; Edgett et al., 2012), and Remote Micro-Imager (RMI; Maurice et al.,
2012) were used to identify and measure features from outcrop- (Navcam and Mastcam) to
grain-scales (MAHLI and RMI). The elevation and location of each observation were determined
from a digital elevation model created from High Resolution Imaging Science Experiment
(HiRISE) stereo pair images (Calef & Parker, 2016; McEwen et al., 2007) and accessed through
the Multi-Mission Geographic Information System (MMGIS) interface (Calef et al., 2017; 2019).

3.1.3 Lamination thickness and grain size

Lamination thicknesses were measured on Mastcam and MAHLI images orthogonal to
bedrock using ImageJ software (Rasband, https://imagej.nih.gov). Methods utilized are similar to
those of other studies at Gale crater where the distance between centers of successive laminae
were measured in pixels and converted to millimeters based on the image resolution (Hurowitz et
al., 2017; Stack et al., 2019; Edgar et al., 2020). Laminae boundaries were estimated when
assessing images with greater standoff distances and lower resolutions. Grayscale pixel intensity
was assessed as a proxy for laminae thickness on one orthogonal MAHLI image by converting
the image to grayscale and assessing grayscale values across multiple laminae, where changes in
grayscale intensity may signify changes in erosion associated with bedrock properties such as
grain size.

Grains were identified where possible in MAHLI images, but resolution limitations and
the lack of ubiquitous visible grain boundaries prevented statistically significant datasets (Gwizd
et al., 2018). The Gini Index Mean Score (GIMS), a proxy for grain size based on chemical
heterogeneity of bedrock derived from Chemistry and Camera (ChemCam, Wiens et al., 2012)
Laser Induced Breakdown Spectroscopy (LIBS) data (See Rivera-Hernández et al., 2019 for
methodology), was used to supplement interpretations of MAHLI images.
3.2. Geochemistry

Geochemical analyses utilized data acquired with the Alpha Particle X-Ray Spectrometer (APXS). The APXS measures the average composition of a 1.5-to-2 cm diameter field of view (FOV) using particle induced X-Ray emission and X-Ray fluorescence techniques (Campbell et al., 2012; Gellert et al., 2009; Gellert et al., 2015). Major-element abundances are reported in oxide weight percent (wt. %); trace elements are reported in parts per million (ppm). For detailed descriptions of methodology and data calibration, the reader is referred to Campbell et al. (2012) and Gellert et al. (2015).

A total of 26 APXS measurements from the HVm and Km stratigraphy are included in this study. Major, minor, and trace elements for the bedrock targets are listed in Table S1. Measurements with an insufficient integration time and full-width-at-half-maximum (FWHM) of spectra were excluded from analyses (Gellert et al., 2015; VanBommel et al., 2019).

Some measurements are acquired on bedrock which has been brushed with a Dust Removal Tool (DRT). The study by Schmidt et al. (2018) shows that dust is known to have an effect on bedrock composition, particularly with lighter elements, but that measurements on surfaces which have not been brushed with the DRT are still capable of recording the underlying rock composition.

This study generally considers all SO$_3$ to be bound in secondary Ca-, Fe-, or Mg-sulfate, consistent with previous geochemical and mineralogical findings (Achilles et al., 2020; Rampe et al., 2020; Thompson et al., 2020). The oxidation state of Fe (reported as FeO$_{(T)}$) cannot be fully constrained with the APXS instrument, and interpretations of Fe are also considered contextually.
with previous compositional studies of the HVm and Km (Bristow et al., 2018; Mangold et al., 2019; Achilles et al., 2020).

3.3 Geochemical tools: A-CN-K, A-CNK-FM, and AF-CNK-M molar ternary diagrams

Processes along the sediment source-to-sink path, from formation to burial, are recorded in the bulk sediment composition (Johnsson, 1993). Studies have determined the range of expected major elemental signatures representing chemical weathering, transport, and diagenesis in terrestrial (e.g. Fedo et al., 1995; Nesbitt & Young, 1984; Nesbitt & Young, 1996; Fedo et al., 2015) and Martian (e.g. Mangold et al., 2019; McLennan et al., 2005; Siebach et al., 2017) sedimentary systems, which each modify sediment from the original source composition. Ternary diagrams of molar $\text{Al}_2\text{O}_3 - \text{CaO}^* + \text{Na}_2\text{O} - \text{K}_2\text{O}$ (A-CN-K), $\text{Al}_2\text{O}_3 - \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{FeO}_{(T)} + \text{MgO}$ (A-CNK-FM), and $\text{Al}_2\text{O}_3 + \text{FeO}_{(T)} - \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} - \text{MgO}$ (AF-CNK-M) provide ways to visualize the nature and extent of chemical alteration from the source rock and to differentiate compositional signatures associated with weathering, sediment transport, and diagenesis (Figure 3). The molar proportions of major elements correspond to primary ($\text{CaO}$, $\text{Na}_2\text{O}$, $\text{K}_2\text{O}$, $\text{FeO}_{(T)}$, $\text{MgO}$) and secondary ($\text{Al}_2\text{O}_3$, $\text{FeO}_{(T)}$) mineral phases within the whole-rock sample. In each ternary diagram, weathering, sorting, and diagenesis in terrestrial settings generally follow predicted geochemical pathways (e.g. Babechuk et al., 2014; Fedo et al., 1995; Fedo et al., 2015; Nesbitt & Young, 1984). Although geochemical trends within sedimentary systems on Mars reveal compositional differences compared with terrestrial systems (Thorpe et al., 2020), predicted pathways nevertheless form the basis from which to evaluate sediment on Mars. Typical pathways emanate from a starting point, the unaltered source (triangle...
a, Figure 3a-c), which may be a composite of several source rock compositions (e.g. different lava flows).

Chemical weathering of basaltic source rocks produces predictable geochemical trends that coincide with enrichment in secondary alteration phases as a result of hydrolysis (Figure 3a-c; Babechuk et al., 2014; Nesbitt & Wilson, 1992; Nesbitt & Young, 1984). Conventional quantities that measure the extent of weathering include the chemical index of alteration (CIA; equation 1; Nesbitt & Young, 1982; Fedo et al., 1995) and the mafic index of alteration (MIA\(\text{O}\) and MIA\(\text{R}\); equations 2 & 3; Babechuk et al., 2014), both of which can be portrayed on the A-CN-K diagram (Figure 3a) and A-CNK-FM and AF-CNK-M diagrams (Figure 3b-c), respectively:

\[
\text{CIA} = \frac{\text{Al}_2\text{O}_3}{(\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O})} \times 100
\]

\[
\text{MIA}_{\text{O}} = \left[\frac{(\text{Al}_2\text{O}_3 + \text{FeO}_\text{T})}{(\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{MgO} + \text{FeO}_\text{T})}\right] \times 100
\]

\[
\text{MIA}_{\text{R}} = \left[\frac{\text{Al}_2\text{O}_3}{(\text{Al}_2\text{O}_3 + \text{CaO}^* + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{MgO} + \text{FeO}_\text{T})}\right] \times 100
\]

Equation 2 pertains to oxidizing conditions (Fe\(^{3+}\)) and includes FeO\(_\text{T}\) in the numerator, and equation 3 pertains to reducing conditions (Fe\(^{2+}\)) and does not include FeO\(_\text{T}\) in the numerator (Babechuk et al., 2014; Thorpe & Hurowitz, 2020). Unweathered basalts typically have CIA values that range from 35-40 (Babechuk et al., 2014). The MIA\(_{\text{O}}\) generally follows the CIA, although it may vary depending on the behavior of Fe and Mg during clay formation, whereas the MIA\(_{\text{R}}\) is lower than the CIA and MIA\(_{\text{O}}\) (Babechuk et al., 2014). Weathered samples (triangle b, Figure 3a-c) will have greater values of CIA and MIA\(_{\text{O,R}}\) compared to the
unweathered source composition (triangle a, Figure 3a-c), and plot along weathering pathways toward greater enrichment in clays (e.g. kaolinite; arrow 1, Figure 3a-c).

The presence of hematite and dioctahedral smectite measured with CheMin from three drill samples, (1) Oudam (Facies 1), (2) Marimba- (Facies 3), and (3) Quela (Facies 3), are indicative of more oxidizing conditions (Achilles et al., 2020; Bristow et al., 2018). Mangold et al. (2019) estimated the Fe$^{2+}$/Fe$^{3+}$ ratio from the Marimba drill sample at 0.059, highlighting the predominance of ferric oxides and supporting the assumption that pre- and post-burial conditions were largely oxidizing, though it is recognized that amorphous Fe-bearing phases increase the uncertainty of the Fe redox state. This study considers iron to mostly represent Fe$^{3+}$ and utilizes the MIA$_{(O)}$ (equation 2) instead of MIA$_{(R)}$ (equation 3).

In addition to primary non-silicate phases (e.g. apatite), cementation and late-stage diagenetic fluid flow enriches bedrock in diagenetic non-silicate phases (Achilles et al., 2020), with one of the most common being Ca-sulfate (Kronyak et al., 2019; Sun et al., 2019). In the ternary diagrams in Figure 3, enrichment in Ca-sulfate drives datapoints along pathways (arrow 2, Figure 3a-c) toward the CN or CNK apices, lowering the apparent degree of weathering (triangle d, Figure 3a; triangle c, Figure 3b-c). The value for CaO$^*$ using molecular proportions in equations 1-3 is conventionally calculated by subtracting the stoichiometric proportion of CO$_2$ and P$_2$O$_5$, which are representative of non-silicate Ca-bearing phases (calcite [Cal] and apatite [Ap], respectively; Fedo et al., 1995; mineral abbreviations from Whitney & Evans, 2010). Carbonates were not detected from CheMin analyses of HVm and Km drill samples, so there is no calcite correction to make. Apatite was also not detected, although P$_2$O$_5$ was measured in all APXS targets ranging from 0.48-1.36 wt% (Table S1) and interpreted in the amorphous fraction (Achilles et al., 2020), making an exact correction uncertain. While secondary Ca-sulfates are
common throughout Gale crater stratigraphy (e.g. Kronyak et al., 2019; Sun et al., 2019), some studies (McLennan et al., 2014; Siebach et al., 2017) do not remove Ca associated with sulfate and interpret geochemical trends with this consideration. Other studies filter out geochemical targets based on identification of diagenetic features in images (Mangold et al., 2019) or choose representative end-members to evaluate weathering extent (Thorpe et al., 2020). When no correction is made, the value of CaO* is equal to the measured wt% of CaO (equation 4):

\[
\text{Uncorrected: } \text{CaO}^* = \text{CaO}_{(T)}
\]  

(4)

In this study, CaO* corrected for apatite and sulfate was determined by assigning P2O5 to apatite and some fraction of SO3 to Ca-sulfate given its common occurrence. This study evaluates a range of possible sulfate corrections because, although CaO and SO3 occur in a 1:1 molar ratio, the subtraction of all SO3 results in a negative or zero value for CaO* for the majority of APXS targets. The presence of Ca-bearing silicate phases as determined by CheMin (Achilles et al., 2020) means that CaO* cannot be zero. Accordingly, we modeled the subtraction of SO3 multiplied by \( n + 0.1 \), where \( 0 \leq n \leq 0.9 \) in order to show the range of possible SO3 outcomes. In this paper, \( n = 0.4 \) is interpreted as the maximum possible correction where \( \text{CaO}^* > 0 \), leaving calcium assignable to silicates (discussed in section 6.1). The resultant equation used in this study to correct for P2O5 and the SO3 phases is (equation 5):

\[
\text{Corrected: } \text{CaO}^* = \text{CaO}_{(T)} - (3.33*\text{P}_2\text{O}_5) [\text{Ap}] - (0.4*\text{SO}_3) [\text{Ca-sulfate}]
\]  

(5)
During sedimentary transport, sorting of basaltic sediment causes relatively finer-grained olivines and pyroxenes (Fe\(^{2+}\), Mg\(^{2+}\), some Ca\(^{2+}\)) to be transported and deposited alongside coarser-grained feldspars (Ca\(^{2+}\), Na\(^{+}\)) that are hydrodynamically equivalent (Fedo et al., 2015; McGlynn et al., 2012; Nesbitt & Young, 1996; Siebach et al., 2017). The record of sorting is harder to differentiate in mafic lithologies using the feldspar-focused A-CN-K ternary diagram, although identification of size-fraction differences between finer grained phyllosilicates and coarser-grained primary phases (e.g. plagioclase) could be reasonably expected. Whole-rock samples unmix approximately along the linear trend emanating from triangle e in Figure 3a (arrow 3) Within the A-CN-K-FM and AF-CNK-M ternary diagrams, sorting of basaltic sediment typically produces the linear trend between finer grained mafic phases and coarser grained feldspars (arrow 3, Figure 3a-b)

Another burial process we consider is potassium metasomatism, which causes the conversion of aluminous clays (e.g. kaolinite) to illite, or the conversion of plagioclase to K-feldspar (Fedo et al., 1995; Yen et al., 2018). Within the A-CN-K, A-CNK-FM, and AF-CNK-M ternary diagrams, the conversion to illite causes datapoints to shift toward the K apex, lowering the apparent CIA. This process is illustrated in Figure 3a by the shift from triangles b and d to triangle c along the dashed arrow 4, and in Figure 3b-c by the shift from triangle a to triangle c along dashed arrow 2.

3.4 Member contacts

Geologic contacts were mapped at the Pahrump Hills-Hartmann’s Valley (PHm-HVm), Hartmann’s Valley-Karasburg (HVm-Km), and Karasburg-Sutton Island member (Km-Sim) boundaries (Figure 1b, dashed white lines) and expand on iterative efforts of the MSL
Sedimentology and Stratigraphy Working Group. Interpretations are based on changes in facies, lithology, and other observable bedrock properties such as a relative increase in the degree of erosion and fracturing in overlying stratigraphic members. Increased bedrock erosion correlates to a greater degree of inundation by sand, causing bedrock to appear relatively duller in orbital images (Figure 4). The contact between the apparently brighter PHm bedrock (Figure 4a) and the apparently duller, more fractured HVm bedrock (-4436 m; Figure 4b) is identifiable in HiRISE and Mastcam images (Figure S1), and correlates with the first appearance of cross-stratified facies (Section 4.1) characteristic of the HVm. The contact cannot be distinguished in the region west of the Naukluft Plateau from orbit or rover-based images due to sand cover and the occurrence of the overlying Stimson formation.

The HVm-Km contact (-4412 m) is inferred based on lithologic differences between the coarser facies of the HVm and the planar-laminated mudstone facies within the Km (detailed in section 4). The Km bedrock is relatively more eroded and fractured (Figure 4c) and lacks the ridged topography characteristic of the HVm landscape (Figure 1b). Obvious changes in bedrock properties at the HVm-Km facies boundary are not observable, and so the mapped contact between the HVm and Km is an approximation from orbital and rover images.

The Km-Sim contact (-4372 m) is also primarily inferred based on lithologic differences. The Sim bedrock (Figure 4d) appears relatively more eroded compared to the Km bedrock. Changes in the degree of erosion are not apparent at the lithologic boundary, and the mapped contact between the Km and Sim is also approximately located using orbital and rover images.

4. Sedimentary lithofacies
Three sedimentary lithofacies were identified within the HVm and Km stratigraphic succession utilizing μm-cm-scale bedrock textures, grain size, laminae, sedimentary structures, and other observable outcrop-scale characteristics (Table S2; Figures 5-8). Facies are presented in order of first appearance within the stratigraphy (Figure 5).

4.1 Facies 1: Cross-stratified sandstone

4.1.1 Description

Exposures of the cross-stratified sandstone facies were identified at multiple levels within both stratigraphic members from the base (Curiosity mission Sol 1104) to the contact between the Km and Sim (Sol 1470; Figures 1, 2, & 5). The majority of outcrops were imaged at distances of ~15-50 m from the rover, which prevented an assessment of contacts with underlying and overlying facies. Exposures are not laterally continuous beyond individual outcrops, though data collected over multiple rover transects both east and west of the Naukluft Plateau suggest that some lateral continuity is possible (Figure 2). The thickness of stratigraphic intervals across both members ranges from 1-4 m (Figure 5). Mineralogical data for Facies 1 was acquired from CheMin analyses of the drill sample Oudam (~4435 m).

Facies 1 is characterized by the presence of trough cross-bedding (Table S2; Figure 6). Truncation surfaces are sub-horizontal with respect to the bounded laminae and are traceable across oblique m-scale outcrops (Figure 6a-b), disrupted by erosion as well as localized cross-cutting veins and nodules. Where truncation surfaces are less distinct, sets were interpreted from apparent changes in dip angle and direction (Figure 6c-d). Measurements of set thicknesses for outcrops with obscured or eroded upper and lower truncation surfaces represent minimum bounds for bedform height derived from individual outcrop heights and range from 50 to 100 cm.
Sets primarily consist of uniform curvilinear laminae. In several exposures, foresets curve and are asymptotic to the underlying strata (white box, Figure 6a, white box). Laminae that appear less curvilinear likely represent a portion of the foreset (Figure 6c). Outcrop orientation and imaging distance prevented measurements of laminae thickness, but comparisons of laminae with overall outcrop scale broadly constrain thicknesses to be mm-cm thick.

The majority of grain boundaries are not resolvable even in the highest-resolution MAHLI images (~15 µm/px). Limited measurements ranging in size from coarse silt to medium sand (Gwizd et al., 2018) are consistent with GIMS data across Facies 1 (Rivera-Hernández et al., 2020). One MAHLI image of the bedrock target Sacajawea consists of pervasive dark-toned and light-toned medium sand grains (Figure S2). A rough surface texture observed in Mastcam and MAHLI images of the bedrock surface provides further evidence suggesting a sand-sized component in Facies 1.

4.1.2 Interpretation

Facies 1 is interpreted to represent a wet aeolian dune field. Preserved structures represent dune foresets and truncation surfaces, which remain after erosion of the stoss and upper lee slope by overlying dune migration (Brookfield, 1977; Rubin & Hunter, 1982). The apparent uniform laminae thicknesses and lack of discernable grain-size differences between outcrops suggests that deposition of laminae across all outcrops may have involved a similar depositional processes, although specific rainfall, grainflow, or wind-ripple deposits cannot be confidently differentiated. Grain measurements include some evidence for coarse silt (Gwizd et al., 2018), but mm-scale rough bedrock textures and pervasive fine sand grains in the target Sacajawea suggest that sand constitutes a primary size fraction. Mud-aggregate lunette dunes have been
observed in terrestrial settings, typically in arid environments, and are associated with desiccation (Bowler, 1973; Greeley, 1979). Rough textures and observations of sand-sized grains as well as a lack of any evidence for widespread desiccation structures associated with Facies 1 suggest that dunes are more likely comprised of a sand-sized component, rather than mud aggregates. Polishing from aeolian abrasion and overprinting by diagenetic mineralization could explain the absence of visible grain boundaries in certain images (Grotzinger et al., 2005; Gwizd et al., 2018).

The thicknesses and distribution of intervals of Facies 1 resemble stratigraphic records of wet aeolian environments (Mountney, 2012). Dune deposition and preservation in wet environments are controlled by increased sediment cohesion from fluctuations in the groundwater table which acts to stabilize dunes and limit dune growth (Kocurek & Havholm, 1993). This process has been documented in arid (Kocurek et al., 2007), sub-humid (Luna et al., 2012), and humid (Mountney & Russell, 2009) environments. Compared with counterparts formed in more arid environments, dunes deposited proximal to a subaqueous environments such as a coastal setting are generally smaller and more spatially isolated (Mountney & Russell, 2009) and comprise relatively thinner stratigraphic intervals (Al-Masrahy & Mountney, 2015; Mountney & Jagger, 2004). The limited thickness of stratigraphic intervals of Facies 1 (< 5 m) is similar to terrestrial records of marginal aeolian dune environments, indicating that dunes may have been comparably spatially isolated across the landscape.

Cross-stratification as described above may also form in fluvial environments, but this interpretation is considered less likely for several reasons. Sets with thicknesses of 1 m are indicative of potential water depths of >10 m, which corresponds to depths in some of the largest terrestrial river systems (Cisneros et al., 2020; Leclair & Bridge, 2001). Given the proximity of
Facies 1 with Facies 3 and the lacustrine basin environment (section 4.3; Figure 5), such a large-scale river system would be unlikely. Additionally, there is an absence of evidence for fluvial architectural elements such as channel fills, accretion elements, and barforms within the stratigraphy (e.g. Ielpi and Rainbird, 2015; Long, 2006; Muhlbauer et al., 2020). Additionally, fluvial facies identified in the Bradbury group consist of granule- and pebble-sized clasts and exhibit varying degrees of sorting (Edgar et al., 2017; Williams et al., 2013). Even where grain boundaries are not visible in MAHLI images, rougher surface textures lack evidence for features in this size range. Altogether, these lines of evidence do not favor a fluvial interpretation.

4.2 Facies 2: Planar-laminated sandstone

4.2.1 Description

Exposures of planar-laminated sandstone were observed throughout the HVm and extend to the contact with Facies 3 and the Km (Figures 2 & 5). Stratigraphic intervals of Facies 2 are most commonly intercalated with Facies 1 (Figure 5). Thicknesses of intervals range from 1.5-8 m and cumulatively represent half of the stratigraphy in the 25 m thick HVm (Figure 5). No drill samples were analyzed by CheMin from Facies 2.

Facies 2 is characterized by continuous accumulations of parallel-laminated sandstone (Figure 7). Where exposed in cross-section, individual laminae are laterally continuous across the outcrop and can be traced across fractures, veins, and patches of sand cover (Figure 7a). Some outcrops consist of intervals of alternating resistant and recessive laminae (Figure 7a) whereas laminae in other outcrops exhibit a similar resistance to erosion (Figure 7b). Laminae measured from one rock target have an average thickness of 1.8 mm ± 0.38 mm (Table S3).
Though measurements were restricted to one target, visual comparisons suggest that this value is broadly representative of mm-scale laminae of Facies 2 across the study region.

Grains are not resolvable in MAHLI images, but several observations support a sand-grade component in contrast to laminated mud. Relative to the planar-laminated mudstone facies (Facies 3, Section 4.3), laminae exhibit a greater resistance to erosion (Figure 7a-b), which may correlate with a coarser grain-size. Additionally, a rough surface texture similar to the cross-stratified sandstone facies was documented in MAHLI images of the bedrock surface (Figure 7c). In addition to sand, a finer grain-size component is supported by GIMS values, which range from mud to sand (Rivera-Hernández et al., 2020). Visual observations support a coarser sand component as the dominant lithology, but a range of grain sizes is considered in interpretations of depositional environments.

4.2.2 Interpretation

The most plausible model for deposition of Facies 2 involves a mixture of subaerial and subaqueous processes. Successions of flat-lying subaqueous and subaerial laminae can accumulate in wet interdune environments where the lowermost toeset laminae of dunes become subaquously reworked or preserved (Langford & Chan, 1989; Mountney & Jagger, 2004; Mountney & Russell, 2009). Although aeolian and interdune components cannot be distinguished within the intervals of Facies 2, modern and ancient studies of wet aeolian systems show that both subenvironments are intricately linked and that a dynamic set of depositional conditions may have produced the planar-laminated strata. In wet aeolian settings, groundwater flooding and fluvial incursion through aeolian deposits can generate laterally expansive ponded interdune environments (Mountney & Jagger, 2004; Mountney & Russell, 2009; Mountney,
Deposition may therefore represent a combination of subaerial reworking, fluvial traction deposition, flooding, and localized sediment grain flows at the edge of interdune hollows. Although there is no documented evidence of preserved flow structures in the HVm to indicate large-scale changes in flow velocity, variability in the erosional resistance of laminae (Figure 7a) may correlate to localized changes in depositional energy.

Studies of terrestrial deposits interpret the intercalation of dune facies with thick intervals of interdune facies to indicate a water-table controlled system typically along outer erg margins (Al-Masrahy & Mountney, 2015; Mountney & Jagger, 2004). The stratigraphic stacking pattern of a water-table controlled aeolian system reflects numerous factors including sediment supply, water-table rise, local dune morphology, and climate (Mountney & Jagger, 2004; ). Successions of comparably thick intervals of dune and interdune facies are indicative of sub-critically climbing strata, typically resulting from the lateral expansion of wet interdune environments and subsequent restriction in sediment supply (Mountney, 2012).

Laminae can form in sandstone from numerous depositional processes, but the thickness of stratigraphic intervals can help constrain depositional processes responsible for Facies 2. Given the apparently significant lateral extent of Facies 2 documented along the HVm traverse (Figures 1 & 2), laminae likely formed via subaqueous deposition. The stratal stacking pattern of planar-laminae and intervals of comparably thick cross-stratified sandstone facies suggests that a subaqueous interdune setting within a wet aeolian system provides the most plausible model for Facies 2. Modes of sediment deposition in wet interdune systems will vary based on the nature of the interdune environment, with common modes of deposition including subaqueous reworking of adjacent dune toeset strata and input from fluvial suspended load and bedload (Mountney & Russell, 2009). Comparably thick intervals of planar laminae can form from suspension fallout in
a lacustrine basin (e.g. Boulesteix et al., 2019), but such an interpretation cannot explain the intercalations with intervals of cross-stratified sandstone (Figure 5). Upper-flow-regime subaqueous conditions are capable of producing horizontal laminae in river systems associated with sporadic flooding, but laminae typically occur in cm-scale packages and are associated with largely arid environments (Colombera & Mountney, 2019; McKee et al., 1967). Subaerial wind-ripple migration can generate meter-thick successions of planar-laminated sandstone associated with interdunes in a dry erg setting (Clemmensen & Abrahamsen, 1983; Hunter, 1977), but the relatively thin intervals of interbedded cross-stratified sandstone facies would be expected to be much thicker in a dry erg setting (Mountney, 2012). Given the thickness of stratigraphic intervals comprising Facies 2, a wet interdune setting is a plausible interpretation of environment, with numerous possible processes responsible for deposition of sediment.

4.3 Facies 3: Planar-laminated mudstone

4.3.1 Description

Exposures of planar-laminated mudstone occur only in the Km stratigraphy (Figures 2 & 5). Outcrops are consistent with the eroded and fractured bedrock characteristic of the orbital images of Km stratigraphy (Figures 1 & 4), suggesting lateral continuity across the study area. Facies 3 occurs in three stratigraphic intervals 3.5, 14, and 16.5 m thick, which cumulatively represent 85% of the Km stratigraphy (Figure 5). Three 1-4 m thick intervals of Facies 1 are associated with Facies 3 at -4409, -4394, and -4376 m (Figure 5). Mineralogical data for Facies 3 was acquired from CheMin analyses of two drill samples, Marimba (-4410 m) and Quela (-4379 m).
Outcrops are comprised of continuous successions of parallel laminae that appear distinctly more recessive and erodible relative to parallel laminae in Facies 2 (Figure 8). The majority of laminae are distinguishable by subtle changes in erosional resistance. Laminae display relatively uniform thickness across the majority of the stratigraphic succession (Figure 8a). Individual laminae measured from three representative rock targets have average thicknesses of 1.3 mm ± 0.2 mm and 2.0 ± 0.5 mm, and 9.1 ± 2.4 mm (Table S3). Apparent thicker and more erosionally resistant laminae were identified at two stratigraphic intervals (-4410 m and -4380 m; Figures 5 & 8b), but the majority of Facies 3 is characterized by mm-scale recessive laminae.

Individual laminae are traceable laterally across outcrops except where disrupted by cross-cutting fractures, veins, or concretions. Laminae show variable resistance to weathering, but overall are more recessive than the planar-laminated sandstone facies. Randomly distributed resistant laminae are characterized by sharp boundaries which are generally associated with diagenetic textures (Figure 8c). Recessive laminae lack diagenetic textures and are generally smooth (Figure 8d). Transects of gray-scale values perpendicular to the recessive MAHLI target Biula show fluctuations in intensity occurring on a similar scale as individual laminae (Figure 8d; Table S3). This similarity in scale indicates that individual laminae correspond to changes in erosion. Intensity values do not reveal gradational patterns characteristic of specific depositional processes, such as tempestites or turbidites (Lazar et al., 2015).

Individual grains are not resolvable in MAHLI images of laminae or bedrock surfaces. The relatively smooth texture and recessive appearance of laminae (Figure 8) suggests that Facies 3 is fine-grained and that the lack of visible grain boundaries corresponds to sediment in the mud size fraction rather than overprinting from erosion or diagenetic textures. More than
50% of GIMS values fall in the mud-to-very fine sand-size fraction, though some component of coarser sand is also indicated by GIMS values, (Rivera-Hernández et al., 2020). A finer-grained component is also supported by mineralogy of Marimba and Quela, which contain a greater amount of clay minerals (28 wt% and 16 wt%, respectively) relative to the Oudam drill sample of Facies 1 (3 wt%; Achilles et al., 2020; Bristow et al., 2018).

4.3.2 Interpretation

Facies 3 is interpreted to have formed primarily from deposition of sediment in a lacustrine environment. The alternating resistant and recessive laminae (Figure 8c-d) resemble the expression of graded laminae where the fine-grained layers are more susceptible to erosion. Successions of graded varves form in glacial lacustrine settings from depositional processes which are controlled by regular changes in runoff and sediment input (Anderson & Dean, 1988).

Thicker laminae could represent localized changes in sediment input or energy (Figure 8b), but their sparse occurrence indicates that environments were largely stable. The lateral continuity and mm-scale thickness of individual laminae are consistent with deposition from hypopycnal, homopycnal, or distal lofted hyperpycnal flow processes (Boulesteix et al., 2019), though the lack of any additional sedimentary structures precludes differentiation of the specific flows responsible for deposition. Subaqueous settling of wind-blown sediment (e.g. loess, ash) could also comprise some of this facies, but the uniform laminae thicknesses and resemblance to clastic varves suggest that laminae formed in response to allogenic or autogenic controls in sediment input (Renaut & Gierlowski-Kordesch, 2010; Zolitschka et al., 2015). Similar depositional processes are attributed to planar-laminated mudstone facies with similar outcrop expressions and laminae thicknesses in underlying and overlying members of the Murray formation (Edgar et
al., 2020; Stack et al., 2019), suggesting that driving mechanisms behind sedimentation of Facies 3 may have been related.

The complete lack of evidence for subaerial exposure indicates deposition in a relatively stable depth of standing water throughout deposition of Facies 3. Terrestrial records of similar lacustrine environments typically exhibit a fluvial-deltaic facies association (e.g. Bohacs et al., 2007). The association of Km mudstone with aeolian facies does not preclude the presence of continuous standing water and may be comparable to ancient and modern unvegetated landscapes, which are associated with an increased sediment supply available for aeolian transport (e.g. Hadlari et al., 2006; Luna et al., 2012; Mountney & Russell, 2009).

5. Stratigraphic and depositional synthesis

Small-to-large-scale observations of the HVm and Km reveal three facies that indicate lacustrine-margin and lacustrine-basin paleoenvironments (Figures 6-8; Table S2). A block diagram of the interpreted landscape is depicted in Figure 9. Cross-stratified and planar-laminated sandstone facies are interpreted to represent deposition of aeolian dunes and subaqueous ponded interdunes along the lacustrine margin (Figures 6 & 7). Although the depiction of cross-stratified sandstone facies in the Km portion of the stratigraphic column shows apparent interbedding with the lacustrine mudstone facies (Figure 5), the lack of stratigraphic evidence for associated widespread desiccation suggests that m-thick intervals of aeolian dune facies in the Km also represent deposition along the lacustrine margin (Figure 9). The lacustrine mudstone facies represents deposition in a lake basin in the presence of continuous standing water (Figures 8 & 9). Deposition is interpreted to be controlled by fluvial generation of sediment flows and plumes within the basin (Mulder & Zyvitski, 1995; Zavala et al., 2011),
which implies that fluvial-deltaic environments occurred within the lacustrine-margin landscape (Figure 9). It is noted that fluvial-deltaic facies were not documented in the stratigraphy of the HVm and Km, but do occupy intervals within the underlying Pahrump Hills member (Stack et al., 2019) and Bradbury group (Grotzinger et al., 2015).

Comparisons with analogous terrestrial environments provide a basis for spatial constraints of the landscape depicted in Figure 9. The Skeiðarársandur glacial outwash plain in south Iceland and the Lençóis Maranhenses coastal dune system in northeast Brazil are modern analogues for wet aeolian environments adjacent to a coastline (Hilbert et al., 2016; Mountney & Russell, 2009). Wet aeolian environments in the Skeiðarársandur plain are characterized by isolated dunes with heights up to 3 m and small dune fields (up to 1 km$^2$) with heights up to 5 m, and subaqueous interdunes characterized by low energy fluvial streams and ponds of up to 0.3 m of standing water (Mountney & Russell, 2009). The Lençóis Maranhenses dune system comprises an area of 1052 km$^2$ and is characterized by dunes with heights of 50-100 cm proximal to the coast and reaching up to 30 m downwind (Parteli et al., 2006). Interdune ponds reach maximum depths of ~1 m (Dos Santos et al., 2019). Simplification of the traverse segments across the HVm and Km (Figures 1 & 2) into an E-W segment (Sol 1105-1353) and a N-S segment (Sol 1353-1471) constrains a comparably smaller area of approximately 1.4 km$^2$. Although variable boundary conditions (e.g. climate, tectonics, sediment supply) control the scale of each landscape (Ewing & Kocurek, 2010), the overall scales over which facies transitions are documented in both environments are comparable in scale of transitions across the study area. These environments may therefore provide plausible scenarios for the extent of the marginal landscapes beyond the region of the rover traverse.
Although spatial characteristics (e.g. areal extent, water depth) of lake systems do not directly relate to stratal stacking patterns (Bohacs et al., 2000), terrestrial studies can be used to constrain aspects of the HVm and Km stratigraphy. The continuity and uniformity of mudstone laminae and the lack of stratigraphic evidence for flooding or desiccation in the Km is consistent with terrestrial records of overfilled lake basins (e.g. Bohacs et al., 2007; Stewart & Mauk, 2017). Whereas the underlying PHm stratigraphy exhibits a progradational trend (Carroll & Bohacs, 1999; Bohacs et al., 2000), the HVm and Km stratigraphy exhibits an overall trend toward finer-grained lacustrine mudstone with intervals of aeolian sandstone at stratigraphically higher elevations (Figure 5), suggesting that the stratigraphy of the HVm and Km record an interval of lake expansion.

6. Linking depositional conditions and composition

6.1 APXS dataset

Twenty-nine APXS measurements of whole-rock geochemistry (Table S1) from the HVm and Km are utilized to explore the possible fingerprints of source-rock composition, chemical weathering, sorting, and diagenesis. In order more accurately evaluate the primary geochemical trends, data are discussed bracketed by two end-member scenarios: with (equation 5) and without (equation 4) a correction for apatite and Ca-sulfate (section 3.3). Based on the occurrence of primary Ca-bearing silicate phases measured with CheMin (Achilles et al., 2020), the upper limit for the fraction of molar SO$_3$ subtracted from Ca is defined where CaO* $\leq$ 0. Within the HVm and Km APXS targets, this threshold occurs at a fraction of 0.5*SO$_3$. Given the relative proportions of primary Ca phases to diagenetic Ca-sulfate measured with CheMin in Oudam, Marimba, and Quela (Achilles et al., 2020), a fraction of 0.4*SO$_3$ is likely too high, but
is a plausible upper bound for a Ca correction. Calculated CIA and MIA(O) indices from each modeled fraction of SO₃ are listed in Table S4. Values of CIA calculated within the range defined by this study are similar to those determined using ChemCam in Mangold et al. (2019), lending further support for the range of modeled corrections in this study. In sections 6.2-6.5, uncorrected data is that where no applied Ca correction (CaO* = CaO(T)) is made, and Ca-corrected data correspond to values of CaO* calculated using the upper limit defined in this study.

6.2 Source rock

The composition and texture of the source rock determines the original starting point to assess all subsequent compositional changes associated with sediment formation and deposition. Though an exact provenance composition for the HVm and Hm facies cannot be determined, a compositional range can be estimated (Figure 10) using the geochemistry of igneous float rocks documented at Gale crater and basalt classes of Gusev crater (Figure 10a; Table S1; McSween et al., 2008). Additional constraints derive from indirect assessments of geochemical trends of Facies 1-3 in A-CN-K ternary space (Figure 10b), which are compared to established alteration trends for basalt (Nesbitt & Wilson, 1992).

A direct assessment of a plausible source composition was done by averaging known Martian basaltic compositions (Figure 10a). Figure 10a includes compositions interpreted to be igneous from Gale and Gusev craters analyzed with the APXS instrument. Float rocks (n = 19) identified along the Curiosity traverse represent a diverse assemblage of alkaline and basaltic compositions (Table S1; Berger et al., 2020; Schmidt et al., 2014; Thompson et al., 2016; Wiens et al., 2020). Basalts (n = 16) documented at Gusev crater are defined by their geochemistry and
include the Adirondack, Irvine, Wishstone, Backstay, Algonquin, and Barnhill classes (Table S1; Gellert et al., 2006; McSween et al., 2008; Ming et al., 2008). All datapoints were Ca-corrected for apatite. Within the A-CN-K ternary diagram (Figure 10a), Gale float rocks (orange circles) predominantly plot along a CIA range of 36-45, with one datapoint plotting at a CIA of 33 and one datapoint plotting at a CIA of 49. Gusev basalt classes (gray circles) predominantly plot along a CIA range of 37-40, with four datapoints plotting above a CIA of 45 (Figure 10a). An average value of all data points (black filled circle, Figure 10a) was generated as a plausible “homogenized” source rock composition for the HVM and Km facies and plots at a CIA of 42. Also included is the average value for Martian crust (blue filled circle, Figure 10a; Taylor & McLennan, 2009), which is also Ca-corrected for apatite and is similar in composition.

Linear trends produced from chemical weathering of source bedrock (arrow 1, Figure 3a; Nesbitt & Wilson, 1992; Thorpe et al., 2020) can be used as a means to indirectly estimate the original source composition. In the A-CN-K ternary diagram, the lowermost point along the chemical weathering path plots at low values of CIA (the vertical axis of the ternary diagram) and typically represents a measured unaltered source rock composition (triangle a, Figure 3a). Without an exact constraint on the unaltered source rock for the HVM and Km facies, a lower bound may be estimated from linear data arrays in sedimentary rocks that result from erosion of weathered profiles (Nesbitt et al., 1997). Data for each facies define linear arrays (Figure 5b) in A-CN-K space, providing guidance for estimating bulk starting composition where the line of best fit intersects the A-CN join.

Figure 10b shows the distribution of Facies 1-3 with no Ca correction (faded yellow, red, green filled triangles) following equation 4 and with a Ca correction (dark yellow, red, green filled triangles) following equation 5. Both the uncorrected and the corrected data for each facies
plot as linear trends and show a similar range of CIA values between facies in A-CN-K ternary space (Figure 10b), consistent with the geochemical similarities observed across most oxides (Figure S3). The gray box along the y-axis in Figure 10b shows the range of lower bounds for source rock CIA defined by the three facies where the best-fit line intersects the A-CN join. In the uncorrected scenario, the Facies 1 trendline intersects the A-CN join at the lowermost value of $A = 6$ (where $A = $ CIA value), the Facies 2 trendline intersects at $A = 16$, and the Facies 3 trendline intersects at $A = 27$. All intersect points occur below the CIA of the averaged Martian basalt ($A = 42$). In the Ca-corrected dataset, the Facies 1 trendline does not intersect the A-CN join, the Facies 2 trendline intersects at $8$, and the Facies 3 trendline intersects at $29$. Similar to the uncorrected trendlines, both intersects occur below the range of CIA for the averaged Martian basalt. In both scenarios, trendlines intersect the A-CN join at values below the averaged Martian basaltic composition as well as typical unweathered terrestrial basalts ($A = 35-40$; Babechuk et al., 2014).

Extrapolation of the linear trend across all facies results in an approximate intersection at the A-CN join at $A = 18$ for uncorrected data and $A = 10$ for Ca-corrected data, within the range defined by the individual trendlines (Figure 10c). The intersection of both trendlines with the mixing line between a Ca-sulfate end-member and the average basalt source (purple line, Figure 10c) provides additional support for analysis of source composition along the trendlines defined by the uncorrected and corrected data arrays. Both trendlines intersect the averaged Martian basalt source composition (black filled circle, Figure 10c). The geochemical similarity of HVM and Km facies to the averaged basalt indicates that the compositional variability of the Gale float rocks and Gusev basalts captures a plausible range of source compositions. An Adirondack end member and a potassic-rich end member have both been previously suggested to explain the
source composition of intermittent intervals of the Murray formation (Bedford et al., 2019; Edwards et al., 2017), though some component of diagenetic K-rich phases could also cause data to deviate from the A-CN apex (section 6.5; Mangold et al., 2019; Yen et al., 2018). Given the compositional data of basalts and the interpretation of the sedimentary rock data, the averaged basalt value derived from Martian basaltic compositions provides a reasonable estimate of a source rock compositional range for all three HVm and Km facies.

6.3 Weathering

Mineralogical and geochemical trends indicate that chemical weathering has influenced the composition of Murray formation sediments, including the stratigraphy of the HVm and Km (Bristow et al., 2018; Mangold et al., 2019). The extent of chemical weathering for the HVm and Km facies can be understood by contextualizing geochemical trends in ternary diagrams with calculated CIA and MIA$_{(O)}$ indices (section 3.3). Potential weathering trends are illustrated in A-CN-K, A-CNK-FM, and AF-CNK-M ternary diagrams using both uncorrected and Ca-corrected data (section 6.1; Figure 11). The addition of diagenetic Ca-sulfates raises the total calcium abundance, and thus lowers CIA so that the uncorrected data represent the minimum extent of weathering (Figure 11a-c); by contrast, the Ca-corrected data represent the maximum extent of weathering (Figure 11d-f) determined in this study because the correction was set for reaching the point where calcium initially approaches zero (discussed above). Included for comparison are data from the basaltic terrestrial Chhindwara weathering profile (black boxes), a post-Pleistocene and moderately weathered profile developed on Deccan Trap basalt (Babechuk et al., 2014).

Each of the three facies is plotted on the A-CN-K diagram (Figure 11a) as a way to identify whether deposition by differing processes generates changes in perceived weathering.
intensity. Uncorrected data plot sub-parallel to the A-CN join and span a CIA range of about 11 CIA units (A = 34-45; Table S4). Facies 1 data form a linear trend at a CIA range of 34-45 (yellow triangles, Figure 11a). Facies 2 data also form a linear trend, albeit with more scatter relative to Facies 1, along a CIA range of A = 35-43 (red triangles, figure 11a). Similar to Facies 1 and 2, Facies 3 data form a linear trend at a CIA range of A = 36-42 (green triangles, Figure 11a). Uncorrected values of CIA are similar between mud and sand facies (Figure 11a; Table S4). The data exhibit a linear trend similar to the Chhindwara profile but are less extensively spread out, plotting in position at a level similar to corestone-rich horizons (Figure 11a).

As expected, corrected data shift toward the A-apex and plot along a CIA range of about 19 CIA units (A = 42-61), representing an increase in the average CIA of 13 CIA units (Figure 11d). This shift towards A indicates a substantially greater extent of weathering across facies, with a difference of up to 20 CIA units between corrected values and the modeled starting source composition (A = 42; section 6.2). Facies 1 data form a linear trend at a CIA range of A = 42-57 (yellow triangles, Figure 11d). Facies 2 data form a linear trend along a CIA range of A = 48-61 (red triangles, figure 11d). Facies 3 data form a linear trend at a CIA range of A = 52-58 (green triangles, Figure 11d). Corrected values for CIA are similar between mud and sand facies (Figure 11d; Table S4), with both plotting near more weathered intervals of the Chhindwara weathering profile. Data exhibit a difference of up to 19 CIA units relative to the modeled source rock composition (A = 42; section 6.1), suggesting the true extent of weathering was considerable. Given the presence of secondary sulfate in the samples, the corrected data are much more likely to represent the actual compositions at the time of deposition. It is worth noting that the data array shows an increase of K2O across the array, indicative of its subsequent addition. Following the graphical correction approach of Fedo et al. (1995), CIA values in the Ca-corrected data raise
a maximum of about 2-3 units, which we consider negligible, but yields a final range of pre-diagenesis CIA values of 42-62.

On the A-CNK-FM diagram (Figure 11b), facies plot below the feldspar-olivine join and are more clustered compared with the spread of data from the Chhindwara weathering profile. All facies plot more proximal to the FM-apex relative to the averaged basaltic source composition (black circle, Figure 11b). Relative to uncorrected facies, Ca-corrected data shift toward the A-FM axis, with most data points plotting along-to-above the feldspar-olivine join (Figure 11e). Corrected facies overlap within A-CNK-FM ternary space, with a slight trend of Facies 3 toward the FM-A axis relative to Facies 1 and 2. All facies plot further from the averaged source relative to uncorrected facies. Compared to the Chhindwara weathering profile, corrected data remain relatively clustered and do not follow a weathering pathway (Figure 11e). For uncertain reasons, this observation is in contrast with the trends in Figure 11a and Figure 11d, where data appear to plot along a linear trend similar to an expected weathering pathway.

On the AF-CNK-M diagram (Figure 11c), uncorrected facies plot across a range of MIA(O) values from 48-60 (Table S4). Most datapoints plot more proximal to the AF apex compared to the averaged basaltic source composition (black circle, Figure 11c). Facies overlap similarly to the other ternary diagrams, although Facies 2 exhibits a slight trend toward the M-apex and Facies 3 is more clustered toward the AF-apex compared to Facies 1 and 2. Data corrected for non-silicate calcium show a relative increase in the MIA(O) by an average of 5.5 MIA units, with a total range of MIA(O) of 13 units (Table S4). Facies shift toward the AF-M axis and plot more proximal to the AF apex relative to the averaged basaltic source composition (black circle, Figure 11f). Facies generally exhibit a similar degree of overlap compared to the uncorrected values (Figure 11f). Corrected data show a more distinct trend of Facies 2 toward the
M-apex, whereas data from Facies 1 and Facies 3 continue to exhibit a relatively more clustered distribution closer to the AF-apex. The Facies 2 trend coincides with the slightly greater average wt% of MgO (6.34 wt%) relative to Facies 1 (5.90 wt%) and Facies 3 (5.43 wt%). The Chhindwara trend shows the preferential weathering of plagioclase (Ca, Na) over mafic mineral weathering (Mg; Babechuk et al., 2014), which differs from the Mg-apex trend of Facies 2 and the clustered distribution of Facies 1 and 3.

The range of weathering indices and trends using non-silicate Ca-corrected data records variable amounts of chemical weathering across the HVm and Km facies (Figure 11; Table S4). Within the A-CN-K ternary diagram (Figure 11d), moderately extensive chemical weathering is indicated by the range of Ca-corrected CIA values that follow a linear trend similar to that of the Chhindwara weathering profile, indicating the sediments were likely drawn from different levels of a weathering profile or experienced differential chemical weathering during transport and deposition. The geochemical trends and CIA values of Ca-corrected data (Figure 11d) provide evidence for considerable chemical weathering similar to interpretations of ChemCam LIBS for the Murray formation (Mangold et al., 2019). These observations differ from the A-CNK-FM (Figure 11e) and the AF-CNK-M (Figure 11f) ternary diagrams, where facies do not follow a similarly distinct weathering pathway. One important observation is the difference between the relative position of facies relative to the A-apex in A-CN-K (Figure 11a & d) and A-CNK-FM (Figure 11b & e) ternary diagrams. Ternary diagrams for Genoa River mud and sand samples in Nesbitt et al., (1996) depict a somewhat similar scenario between both diagrams, where there is a discernable trend of mud relative to sand toward the A-apex in A-CN-K space but both mud and sand plot at a similar distance from the A-apex in A-CN-K-FM ternary space. The authors attribute these trends as indicative of the effects of sorting of felsic phases (feldspar; Nesbitt et
al., 1996). Although sand and mud facies overlap in A-CN-K ternary space, the difference between trends in Figure 11d and Figure 11e may reflect grain segregation due to sorting in addition to chemical weathering. This apparent discrepancy has been attributed as a shortcoming of the two-dimensional nature of the ternary diagrams (Fedo, 2021), which cannot accurately capture the full range of both felsic and mafic phases and require more context (e.g. mineralogy) when assessing trends.

Given the lacustrine and wet interdune environments interpreted for Facies 1-3 (Figure 9), it is likely that chemical weathering occurred and altered the geochemistry and mineralogy of Hvm and Km sediment, but that other sedimentary processes (e.g. transport, diagenesis) cause the discrepancy between ternary diagrams in Figure 11. One important observation is the difference between the relative position of facies relative to the A-apex in A-CN-K (Figure 11a & d) and A-CNK-FM (Figure 11b & e) ternary diagrams. Regardless, because appraising potential paleoclimate/paleoweathering conditions remains critical to assessing the Martian surface evolution, the above discussion highlights the importance of making Ca corrections for primary and diagenetic non-silicate phases because the extent of sulfates, in particular, may mask the true chemical weathering extent.

6.4 Sorting

Sediment sorting during transport based on grain size and density is a common process known to affect whole rock geochemical signatures of sedimentary deposits. Experimental data and results from studies of modern and ancient basaltic sediment on Earth and Mars define distinct geochemical trends resulting from hydrodynamic sorting where fine-grained and denser mafic grains (e.g. pyroxenes, Fe- and Ti-oxides) are segregated from coarse-grained and less
dense felsic grains (e.g. feldspars; section 3.3; Fedo et al., 2015; Mangold et al., 2011; McGlynn et al., 2012; Siebach et al., 2017; Thorpe et al., 2019). Both fluvial (Garzanti, 1986) and aeolian (Mangold et al., 2011) sediment transport processes are capable of segregating grains based on density, size, and shape, which cause the bulk sedimentary signature to deviate from the original source composition. This process can occur in fluvial settings via segregation of grain size populations in suspended load and bedload as well as within bedload deposits. In aeolian settings, less dense minerals may selectively be entrained in transport, leaving a lag of denser phases (Fedo et al., 2015) or compositional segregation of dunes as detected in Valles Marineris (Chojnacki et al., 2014). Given that Facies 1-3 each represent deposition by processes capable of segregating grains, some compositional change via hydrodynamic sorting is expected to occur.

The relationship between grain size and composition provides the basis from which to evaluate the effects of sorting on the HVm and Km composition.

Several geochemical trends suggest that sorting of grain-size fractions in transport may have influenced bulk geochemical signatures of the HVm and Km facies. Box and whisker plots of wt% oxides show a slight enrichment of Facies 3 in FeO(T), though values overlap with the range of FeO(T) in Facies 1 (Figure S3). This slight relative enrichment is observable in the Ca-corrected A-CNK-FM (Figure 11e) and AF-CNK-M (Figure 11f) ternary diagrams. The enrichment may represent segregation of fine-grained and denser mafic grains during sorting, though CheMin data for Oudam, Marimba, and Quela indicate the presence of diagenetic Fe-bearing phases (Achilles et al., 2020), complicating an interpretation of sorting solely based on Fe. The relative depletion of Facies 3 in wt% MgO (Figure S3) does not correlate with the expected segregation of olivine and pyroxene, but this discrepancy could also be explained by the variable influence of Mg-bearing diagenetic phases (Sun et al., 2019).
Figure 12 compares Al₂O₃ and TiO₂ of the sandstone and mudstone facies to expected trends resulting from chemical weathering and hydrodynamic sorting (Young & Nesbitt, 1998). In the absence of any weathering or hydrodynamic sorting, the distribution of sediment should cluster around a specific source composition. Previous studies have determined that Ti:Al ratios will remain consistent with the original source composition up to moderate levels of chemical weathering (CIA < 80; Nesbitt & Wilson, 1992; Young & Nesbitt, 1998). As grains are transported from continental source rocks, sorting will separate the fine-grained TiO₂-rich fraction from the coarse-grained TiO₂-poor fraction, resulting in the vertical trend indicated by the arrows in Figure 12a. Compared to the expected linear sorting trend, data across all three facies are clustered around a similar range of Al₂O₃ and a much narrower range of TiO₂ (Figure 12). Additionally, all facies plot above the averaged basaltic source composition defined in this study (black dot, Figure 12a). The expanded inset in Figure 12b shows that Facies 3 does not define a completely separate range of greater wt% TiO₂ compared to the Facies 1 and 2, as would be expected for finer grain sizes influenced by sorting. A slight distinction can be made between Facies 3 data points compared with Facies 1, but the overall trend is more clustered compared to model from Young and Nesbitt (1998).

Several factors may explain the overlap between facies in Figure 12. The range of the total grain size population between the facies is likely relatively small (fine sand and smaller) compared with other sedimentary systems where sorting is known to occur (Nesbitt & Young, 1996; Young & Nesbitt, 1998). Comparisons with compositional trends of fluvial-lacustrine (Siebach et al., 2017) and aeolian (Banham et al., 2018; Bedford et al., 2020) stratigraphy of the Bradbury group and Stimson formation, respectively, show substantially greater geochemical variation indicative of sorting compared to the HVm and Km facies. The Bradbury group
consists of grains up to the pebble size fraction (Siebach et al., 2017), and the aeolian Stimson formation consists of grains from very fine to very coarse sand and as well as granule sized grains (Banham et al., 2018). A smaller total range of relatively finer grain sizes across Facies 1-3 may explain the relative distribution of each facies as well as the distribution of facies compared to the averaged source rock in Figure 12.

Another factor to consider is the phenocryst size in the source basalt. An experimental study by Fedo et al. (2015), where two basalt samples were mechanically crushed and sieved to simulate sediment generation and sorting, showed that isolation of individual mineral phases from an aphyric basalt sample occurred beginning at the fine sand to silt sieve fraction, but with overall limited compositional change via sorting. By contrast, a porphyritic basalt sample shows separation of olivine grains from the bulk sediment, which results in substantial compositional change between grain-size fractions. It is therefore possible that the source-rock crystal size was more aphanitic, thus influencing on the amount of variability resulting from sorting.

Nevertheless, contextualization of geochemical trends with interpretations of subaerial and subaqueous depositional processes responsible for Facies 1-3 (Section 4) suggests that hydrodynamic sorting occurred and influenced some component of the geochemical signatures of HVm and Km facies.

### 6.5 Diagenesis

Stratigraphic, mineralogical, and geochemical evidence supports numerous episodes of early- and late-stage diagenetic fluid flow in the Murray formation strata. Previous studies have characterized variable amounts of compositional change on the whole rock geochemical signatures as well as enrichment in precipitated phases from distinct post-depositional fluid flow.
events (Achilles et al., 2020; Bristow et al., 2021; Fraeman et al., 2020; Kronyak et al., 2019; Sun et al., 2019). Contextualization of geochemical trends within HVm and Km facies with the variable amounts of crystalline, phyllosilicate, and amorphous diagenetic phases measured in Oudam, Marimba, and Quela (Achilles et al., 2020; Bristow et al., 2018) and the macro-scale diagenetic features (e.g. veins, concretions; Kronyak et al., 2019; Sun et al., 2019) can place some relative constraints on the extent and composition of diagenetic phases.

Calcium sulfate phases are present throughout the HVm and Km stratigraphy in the form of veins, concretions, and matrix cements (Achilles et al., 2020; Thompson et al., 2020). As previously discussed, the addition of Ca-sulfates leads to significant changes in the geochemistry. Where veins and concretions are not observable within the APXS field of view, the presence of Ca-sulfate cement is supported by the correlation of wt% CaO and SO$_3$ (see Figure S1 of Thompson et al., 2020).

Potassium metasomatism is a common process by which aluminous clays are enriched in K$^+$ and converted to illite (Fedo et al., 1995). Though illite is not demonstrated to represent a significant component of the clays measured with CheMin, the linear trend in Figure 11a shows a slight deviation away from parallel to the A-CN join, which indicates increasing potassium enrichment through diagenesis (Fedo et al., 1995). The trend shown with HVm and Km facies demonstrates that minor diagenetic K-enrichment occurred, in agreement with the findings of Mangold et al. (2019) who calculated the amount of K$^+$ associated with the proportion of sanidine in Marimba and concluded that some fraction of the enrichment may have resulted from illitization.

Mineralogical data from the HVm and Km drill samples indicates a variety of additional diagenetic phases detailed in Achilles et al., 2020 and Bristow et al., 2018. In addition to
hematite, amorphous and nanophase FeO\(_{(T)}\), and SO\(_3\) are interpreted to constitute a significant fraction of the Marimba (16.8%, 3.6%) and Quela (10.5%, 6.1%) mudstones relative to the Oudam sandstone (5.5%, 1.2%; Achilles et al., 2020). Such phases could be the cause of the slight Fe trend in mudstone (Figure 11b-c; Figure S3). Diagenetic phases, which have been well-documented throughout the HVm and Km stratigraphy, represent variable fluid compositions and temperatures of formation and collectively highlight the longevity and diversity of post-depositional fluid events.

7. Discussion: Integrated depositional and compositional pathway

Sedimentologic, stratigraphic, and geochemical interpretations indicate that the HVm and Km facies represent deposition within and along the margin of lacustrine basin during a time consistent with modest, but appreciable, chemical weathering. Such a paleoenvironmental and paleoclimate scenario is similar to those interpreted in both underlying (Stack et al., 2019) and overlying (Caravaca et al., 2022; Edgar et al., 2020) units of the Murray formation. The long-held links between depositional sedimentary processes and whole-rock compositional signatures (Johnsson, 1993) can help to define a source-to-sink history, which we do below for the HVm and Km.

Subsequent to crater formation, the significant topographic gradient along the crater margin acted as both the likely source for sediments and a means to drive deposition downslope into the crater (Figure 9a; Grotzinger et al., 2015). As discussed above and previously considered (Bedford et al., 2019; Edwards et al., 2017), the source rock was basalt, similar to rocks previously encountered at Gale and Gusev craters. Given the comparatively homogenous
composition between sandstones of Facies 1 and 2 and mudstones of Facies 3, it is possible the source basalt could have had an aphyric texture (Fedó et al., 2015).

Chemical (and physical) weathering of the source rock along margin of, and in the watershed feeding the rim (Ehlmann & Buz, 2015) generated sediment with many primary mineral phases mixed with clays formed by chemical weathering (Figure 9a). A precise characterization of climate cannot be constrained from the weathering indices in this study, but the environment had to be capable of effectively making phyllosilicates through hydrolysis and sustaining liquid water in order to carry sediment by tractive processes (Williams et al., 2013) across the basin floor, and into deltaic systems (Grotzinger et al., 2015; Stack et al., 2019) that entered standing water (Edgar et al., 2020; Stack et al., 2019, Edgar). ChemCam LIBS data though the Murray formation suggest similar environmental conditions (Mangold et al., 2019).

All three facies, regardless of grain size, have geochemical compositions that not only overlap, but also define linear trends in A-CN-K compositional space (Figure 11). This type of data scatter suggests that sediments were potentially drawn from a source that exposed multiple levels of a weathering profile, a situation common in non-steady state conditions where rates of physical erosion and mass wasting outpace clay production via chemical weathering (Nesbitt et al., 1997). Studies attribute topographic variability to be a key control over the extent of chemical weathering, with steeper slopes experiencing increased sediment erosion rates and incomplete weathering (e.g. Johnsson & Stallard, 1989; Riebe et al., 2015). Given the relatively steeper topography of the crater rim, an increase of sediment erosion over chemical weathering is expected and observed.

Subsequent to weathering and erosion, sediments would have been transported away from the rim and toward the basin center and subject to physical processing (Figure 9). Steeper
topographic conditions closer to the crater rim likely moved sediment through flooding and mass-wasting events, producing coarse-grained fans (Palucis et al., 2014), which potentially correlate downslope with fluvial deposits of the Bradbury group (Williams et al., 2013). Further along the source-to-sink pathway, sediment transport conditions are dominated by traction transport in fluvial and aeolian environments (Figure 9). Sorting of sediment based on grain size, shape, and density would have resulted in sedimentary compositions differentiating from the source and potentially even from each other in different grain size fractions (Fedo et al., 2015; Garzanti 1986). In the case, of the HVm and Km, the lack of substantial compositional change between facies is attributed to a generally small range of grain sizes between facies and the potential the source itself was texturally homogenous. Temporary storage of sediments in weathering profiles between major depositional episodes could have permitted some additional chemical weathering similar to what was described by Johnsson & Meade (1990) along the transport path may have provided an additional source of weathering to the coarser-grained sand facies, producing the overlapping geochemical trends in Figures 10 through 12.

At the site of deposition along the lacustrine margin and within the lacustrine basin, physical and chemical processes continued to modify sediment composition. The interfingering relationship between dune and interdune facies along the lacustrine margin (Figure 9b) suggests that some degree of sediment mixing between Facies 1 and 2 may have occurred, similar to terrestrial wet dune-interdune relationships (e.g. Mountney & Russell, 2009). This mixing would have homogenized the relative compositions and textures of both sand facies. Facies 3 sediments were deposited in the more marginal regions of the lacustrine basin by subaqueous flows, and subject to further alteration at the site of deposition (Bristow et al., 2018).
Deposition and burial of sediments occurred to sufficient depth for lithification to occur. Diagenetic enrichment in crystalline and amorphous phases occurred from deposition through post-lithification. During burial, a minor amount of potassium metasomatism occurred and enriched the bulk composition in potassium (Fedo et al., 1995). Post-lithification, diagenetic products with variable morphologies and compositions formed from different fluid flow events. One of the most common phases is Ca-sulfate, which occurs as veins, concretions, and matrix cements (Achilles et al., 2020; Sun et al., 2019; Thompson et al., 2020). In addition to primary non-silicate phases (apatite), diagenetic phases can mask additional geochemical signatures, as indicated by the effects of the Ca-correction applied in this study (equation 5).

8. Conclusions

This study provides a detailed stratigraphic and compositional analyses of the 65-m-thick interval comprising the Hartmann’s Valley and Karasburg members of the Murray formation, Gale crater, Mars. Three facies documented from orbital, outcrop, and hand-lens-scale bedrock characteristics include (1) cross-stratified sandstone, (2) planar-laminated sandstone, and (3) planar-laminated mudstone facies. The two sandstone facies are interpreted to represent associated aeolian dune and interdune subenvironments. The absence of evidence for widespread aeolian dunes and other features indicative of desiccation suggests that these facies do not signify a widespread dry interval, but rather constitute relatively isolated aeolian dunes along a lacustrine margin. The planar-laminated mudstone facies comprises the lacustrine facies association and represents deposition from density currents, with seemingly random and sparse intervals of potentially thicker laminae representing changes in depositional energy. The similar outcrop appearance, laminae thickness, and µm-scale textural features between mudstone facies
of the Karasburg member and other mudstone facies in the Murray formation indicate that the planar-laminated mudstone represents similar depositional processes in a lacustrine basin and extends the stratigraphic record of lacustrine environments at Gale crater.

Compositional trends provide additional constraints for the lacustrine and lacustrine margin environments when contextualized with sedimentary processes. Weathering indices and geochemical trends between facies support moderate chemical weathering. Trends between immobile oxides indicate influence from hydrodynamic sorting, which is known to occur in aeolian and fluvial transport systems. Combined compositional and sedimentological observations indicate that the relative location of the Hartmann’s Valley and Karasburg stratigraphy along the source-to-burial path is more proximal to the basin center. This study ultimately extends the range of diverse facies encountered in the Murray formation and provides a refined understanding of a unique period in the history of lacustrine activity at Gale crater.

Acknowledgements:
The authors acknowledge the critical efforts of the Mars Science Laboratory (MSL) Curiosity rover engineering and science operations teams as well as the MSL Sedimentology and Stratigraphy Working Group. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Mastcam mosaics were processed by the Mastcam team at Malin Space Science Systems. We thank two reviewers for the comprehensive feedback that greatly improved the quality of this manuscript. S. Gwizd and C. Fedo acknowledge funding from NASA/JPL subcontract #1546201.
Open research

The code repository for the MMGIS interface can be accessed through (https://github.com/NASA-AMMOS/MMGIS) and is detailed by Calef et al. (2019). The HiRISE mosaic used through the MMGIS interface can be accessed through Calef and Parker (2016). Data derived from HiRISE (McEwen, 2005) and CTX (Malin, 2007) images can also be accessed through the NASA Planetary Data System Geosciences Node (https://pds-geosciences.wustl.edu/missions/mro/default.htm). All Mastcam (Malin, 2013) and MAHLI (Edgett 2013a, 2013b) images used in this manuscript may be accessed through the NASA Planetary Data System Cartography and Imaging Sciences Node (https://pds-imaging.jpl.nasa.gov/volumes/msl.html). All MSL APXS data used in this manuscript can be accessed through the NASA Planetary Data System Geosciences Node (https://pds-geosciences.wustl.edu/missions/msl/index.htm; Gellert, 2013). All MER APXS data used in this manuscript may be accessed through the NASA Planetary Data System Geosciences Node (https://pds-geosciences.wustl.edu/missions/mer/index.htm; Geller, 2019).

References


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Figure Captions

Figure 1. (A) Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) mosaic of Gale crater providing context for Curiosity’s exploration area (white box). (B) Traverse path across the Hartmann’s Valley and Karasburg members of the Murray formation through the beginning
of the traverse across the Sutton Island member. Key formations, features, and stratigraphic contacts are marked. Sol numbers mark the locations of several key outcrops listed in Table S2. The base map is a merged HiRISE orthophoto mosaic from Calef and Parker (2016). (C) Generalized stratigraphic column showing the thickness of the strata in the underlying Bradbury group, the lacustrine Murray formation, and the overlying Carolyn Shoemaker formation. The red bracket indicates the Hartmann’s Valley and Karasburg members. Also included is the unconformable Stimson formation. Modified from the MSL Sedimentology and Stratigraphy Working Group.

**Figure 2.** Topographic profile depicting the distribution of facies along the *Curiosity* rover traverse (Sols 1104-1470) across the Hartmann’s Valley and Karasburg members, including the unconformable Stimson formation (grey). Facies are projected into the subsurface along the first portion of the traverse (~0-1.2 km) to show possible lateral correlations, but are not projected along the second portion of the traverse (~1.2-2.5 km) due to the largely monotonic ascent of the rover. Both segments are separated by the dashed vertical line. See figure 1 for map view of traverse path. Arrows indicate changes in the drive direction along the x-axis. Vertical exaggeration is 10x.

**Figure 3.** (A) A-CN-K (B) A-CNK-FM and (C) AF-CNK-M molar ternary diagrams showing the sedimentary history from (1) source rock (triangle a), (2) weathering along a predicted path (line 1) to greater values of CIA and MIA (triangle b), and diagenetic k-metasomatism and calcium sulfate enrichment (arrows 4 and 2, respectively, in (A) and arrow 2 in (B) and (C)). Within figure (A), a k-enriched composition is represented by triangle c. Within figures (B) and (C), triangle c represents a K- or Ca-enriched composition. Also depicted are expected trends produced from hydrodynamic sorting (line 3). Reference minerals include: Fsp = feldspar; Pl = plagioclase feldspar; Kfs = K-feldspar; Bt = biotite; Ilt = illite; Sme = smectite; Kln = Kaolinite; Gbs = gibbsite; Aug = augite; Ol = olivine; Fe-ox = Fe-oxides. Most mineral abbreviations from Whitney & Evans (2010).

**Figure 4.** Outcrop expressions as viewed from HiRISE, showing representative bedrock of the (A) Pahrump Hills, (B) Hartmann’s Valley, (C) Karasburg, and (D) Sutton Island members highlighting differences in bedrock continuity and erosion between each member.

**Figure 5.** Detailed stratigraphic column for the distribution of Hartmann’s Valley and Karasburg facies.

**Figure 6.** Representative outcrops of the cross-stratified sandstone facies. (A) Outcrop near the contact between the Murray and Stimson formation west of the Naukluft Plateau showing concave laminae (white lines), truncation surfaces (blue lines), and a possible inferred truncation surface (dashed blue line) based on apparent alternating dip directions between adjacent laminae. (M100 Mastcam mosaic, mcam06561, Sol 1353). (B) Baynes Mountain outcrop showing sets of laminae with apparent alternating orientations (M34 Mastcam mosaic, mcam06768, Sol 1381). C) Keetmanshoop outcrop consisting of sets at least 1 meter thick (M100 Mastcam mosaic, mcam06838, Sol 1398). (D) Oblique view of Saddle outcrop showing truncation of laminae (M100 Mastcam mosaic, mcam04883, Sol 1101). Image credit: NASA/JPL-Caltech/MSSS
**Figure 7.** Representative outcrops of the planar-laminated sandstone facies. (A) Outcrop consisting of continuous planar laminae showing varying degrees of erosion. The region within the white box is expanded in (B) to highlight an example of alternating resistant planar laminae (M100 Mastcam mosaic, mcam05228, Sol 1157). (C) Example of a smaller-scale outcrop consisting of a continuous succession of planar laminae. Laminae are highlighted with white lines (M100 Mastcam mosaic, mcam05389, Sol 1189). (D) MAHLI target Koes showing a plan view exposure with a distinctly rough bedrock texture (MAHLI ID: mhli00419, Sol 1380). Image credit: NASA/JPL-Caltech/MSSS

**Figure 8.** Representative outcrops of the planar-laminated mudstone facies. (A) Outcrop Kuito consisting of continuous planar laminae (white lines highlight some examples, M100 Mastcam mosaic, mcam07198, Sol 1455). (B) Examples of thicker cm-scale laminae (white arrows, M100 Mastcam mosaic, mcam07067, Sol 1429). (C) Target Caxito containing smaller-scale alternating resistant (white arrows) and recessive laminae with diagenetic textures (M100 Mastcam image, mcam07170, Sol 1448). (D) MAHLI target Buila with plots of greyscale values highlighting variability in recessive and resistant laminae (white arrows, MAHLI ID: mhli00321, Sol 1436). Image credit: NASA/JPL-Caltech/MSSS

**Figure 9.** (A) Basin-scale landscape showing distal sedimentary processes interpreted in this study. Black box indicates the relative location of the Hartmann’s Valley and Karasburg member environments in (B). (B) Landscape schematic for the lacustrine margin and lacustrine depositional environments represented by the facies of the Hartmann’s Valley and Karasburg members. The depiction of the lake margin stratigraphy is adapted from the model for temporally and spatially variable dune systems from Mountney, 2012 (Figure 4). F1 = Facies 1; F2 = Facies 2; F3 = Facies 3.

**Figure 10.** Evaluation of potential source compositional ranges in A-CN-K ternary diagrams. (A) Plot of Gale igneous float rocks, Gusev basalt classes, average Mars crust, and a calculated average of the float rocks and average Gusev basalt classes (dashed line indicates a CIA of 42). (B) Linear trendlines for individual facies with no Ca correction (faded colors; equation 4) and with the applied Ca correction for P$_2$O$_5$ and 0.4*SO$_3$ (bolded colors; equation 5). Gray triangles indicate the location where uncorrected trendlines intersect the A-CN join, and black triangles indicate the location where Ca-corrected trendlines intersect the A-CN join (dashed lines). The gray box shows the range of lower bounds for source rock CIA defined by Facies 1-3 trendlines. (C) Trendlines for all uncorrected (faded triangles) and corrected (bolded triangles) facies compared to the calculated basalt source composition (black circle) and the lower bounds constrained by trendlines in (B). Also included is a mixing line between Ca-sulfate and the average basalt composition (purple line).

**Figure 11.** Weathering trends illustrated on (A) A-CN-K (B), A-CNK-FM, and (C) AF-CNK-M molar ternary diagrams. The shaded in regions of the triangles correspond to the zoomed in portion in A-F. The left column depicts uncorrected data (equation 4) in (A) A-CN-K, (B) A-CNK-FM, and (C) AF-CNK-M diagrams. The right column depicts Ca-corrected data for P$_2$O$_5$ (Ap) and 0.4*SO$_3$ (Ca-sulfate; equation 5) in (D) A-CN-K, (E) A-CNK-FM, and (F) AF-CNK-M diagrams. A second A-CN-K diagram in (D) includes an example of the visual correction for K-enrichment (See Fedo et al., 1995 for methodology). The terrestrial Chhindwara weathering
profile (black boxes; Babechuk et al., 2014) and the average basaltic source composition (black circle) are included for reference.

**Figure 12.** (A) Al$_2$O$_3$ and TiO$_2$ (wt%) of sandstone and mudstone facies compared to predicted geochemical trends of sorting (adapted from Young & Nesbitt, 1998). (B) expanded view of annotated region in (A). The average basaltic source composition (black circle) is included for reference.