AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL059097

# Wind-blown sandstones cemented by sulfate and clay minerals in Gale Crater, Mars

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**Key Points:**
- Lower Mt. Sharp in Gale Crater exhibits evidence for wind-blown sandstones
- Preserved dune topography is indicative of specific environmental conditions
- Some preserved dunes contain clays, possibly as authigenic cements

**Supporting Information:**
- Figures SA1–SA8, Tables S1, and S2
- Readme

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**Citation:**
Milliken, R. E., R. C. Ewing, W. W. Fischer, and J. Hurowitz (2014), Wind-blown sandstones cemented by sulfate and clay minerals in Gale Crater, Mars, *Geophys. Res. Lett.*, *41*, 1149–1154, doi:10.1002/2013GL059097.

Received 19 DEC 2013
Accepted 30 JAN 2014
Accepted article online 31 JAN 2014
Published online 22 FEB 2014

**Abstract** Gale Crater contains Mount Sharp, a ~5 km thick stratigraphic record of Mars' early environmental history. The strata comprising Mount Sharp are believed to be sedimentary in origin, but the specific depositional environments recorded by the rocks remain speculative. We present orbital evidence for the occurrence of eolian sandstones within Gale Crater and the lower reaches of Mount Sharp, including preservation of wind-blown sand dune topography in sedimentary strata—a phenomenon that is rare on Earth and typically associated with stabilization, rapid sedimentation, transgression, and submergence of the land surface. The preserved bedforms in Gale are associated with clay minerals and elsewhere accompanied by typical dune cross stratification marked by bounding surfaces whose lateral equivalents contain sulfate salts. These observations extend the range of possible habitable environments that may be recorded within Gale Crater and provide hypotheses that can be tested in situ by the Curiosity rover payload.

## 1. Introduction

The ~5 km tall mountain in the central region of Gale Crater, colloquially known as Mount Sharp, contains what may be the thickest exposure of sedimentary rock on Mars. However, the mechanisms responsible for the formation of these rocks remain poorly understood and include lacustrine deposition, accumulation of volcanic ash, eolian deposition, ancient polar deposits, and precipitation from giant springs [*Cabrol et al.*, 1999; *Malin and Edgett*, 2000; *Milliken et al.*, 2010; *Greely and Guest*, 1987; *Schultz and Lutz*, 1988; *Rossi et al.*, 2008; *Thomson et al.*, 2011; *Wray*, 2013; *Kite et al.*, 2013]. Each of these hypotheses carries different implications regarding former habitability and the likelihood for preservation of biosignatures [*Summons et al.*, 2011]. Data collected from *Curiosity* will be important in testing these ideas, but because of the great size of Mount Sharp, orbital observations on the sedimentary processes recorded in its strata are key to expanding and contextualizing discoveries made in situ along the rover traverse path.

Orbitally acquired Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) visible-near-infrared reflectance spectra of the strata in Mount Sharp exhibit absorptions in the 0.4–2.5 μm wavelength range that are consistent with the presence of primary igneous minerals (pyroxene and olivine) as well as Fe-bearing clay minerals, hydrated sulfate salts (likely Mg varieties), and red hematite that occur in specific horizons within the strata [*Milliken et al.*, 2010]. Their detections are restricted to strata in the Lower formation of the mound, which is unconformably overlain by the more dust-covered Upper formation [*Milliken et al.*, 2010]. The presence of hydrous minerals and fluvial geomorphic features [*Milliken et al.*, 2010; *Anderson and Bell*, 2010; *Thomson et al.*, 2011; *Wray*, 2013] suggest liquid water was once present in the crater, but the relative contributions of groundwater versus surface runoff are unknown. The duration and absolute age of this aqueous activity are also largely unknown, but crater counts place the formation of Gale Crater and the Lower formation of Mount Sharp along the Noachian-Hesperian time-stratigraphic boundary (3.5–3.7 Ga) [*Thomson et al.*, 2011].

## 2. Results

Images acquired by the High Resolution Imaging Science Experiment (HiRISE) reveal that some strata within and onlapping the Gale Lower formation are likely sandstones. Strata exposed in cross section in the lowermost portion of the Lower formation exhibit horizontal or low-angle bounding surfaces that are laterally

  

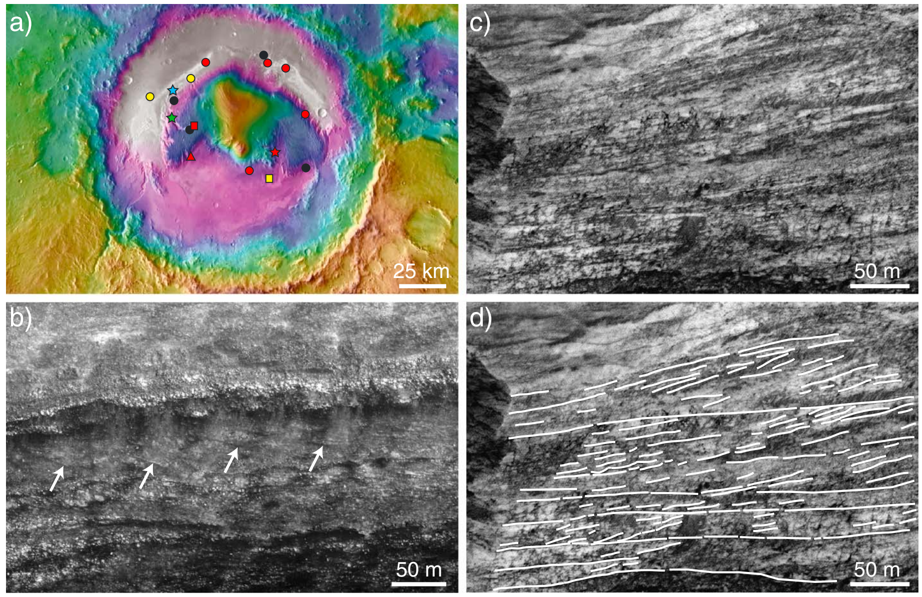


**Figure 1.** The ~155 km diameter Gale Crater on Mars, centered at 137.7°E, 5.3°S. (a) Mars Orbiter Laser Altimeter map overlain on a Context Imager mosaic. Black markers indicate locations of best examples of filled fractures, red indicates locations of preserved bedforms and yellow indicates preserved bedforms with clay signatures. Green star = Figure 1b; blue star = Figure 1c-1d; red triangle = Figure 2a; red square = Figure 2b; red star = Figures 2c–2e; yellow circle = Figure 4; yellow box = Figure SA3,SA4. (b) Dipping beds (white arrows) exhibiting downlap exposed in a canyon in western Mount Sharp. (c) Low-angle bedding observed in the Lower formation of Mount Sharp and (d) interpretation of cross-stratification and bounding surfaces (Figure 1d). Direction of North: (Figure 1a) up, (Figure 1b) left, and (Figures 1c and 1d) down. See Table SA1 for HiRISE image IDs.

continuous over hundreds of meters and separated by tens of meters of inclined stratification (Figure 1 and Figure SA1 in the supporting information). This stratigraphic architecture is interpreted as ~20–40 m thick sets of dune cross stratification. Subcritical angles of bedform climb are documented by foresets truncated by an upper bounding surface and bottomsets that downlap onto a lower bounding surface. CRISM spectra for this

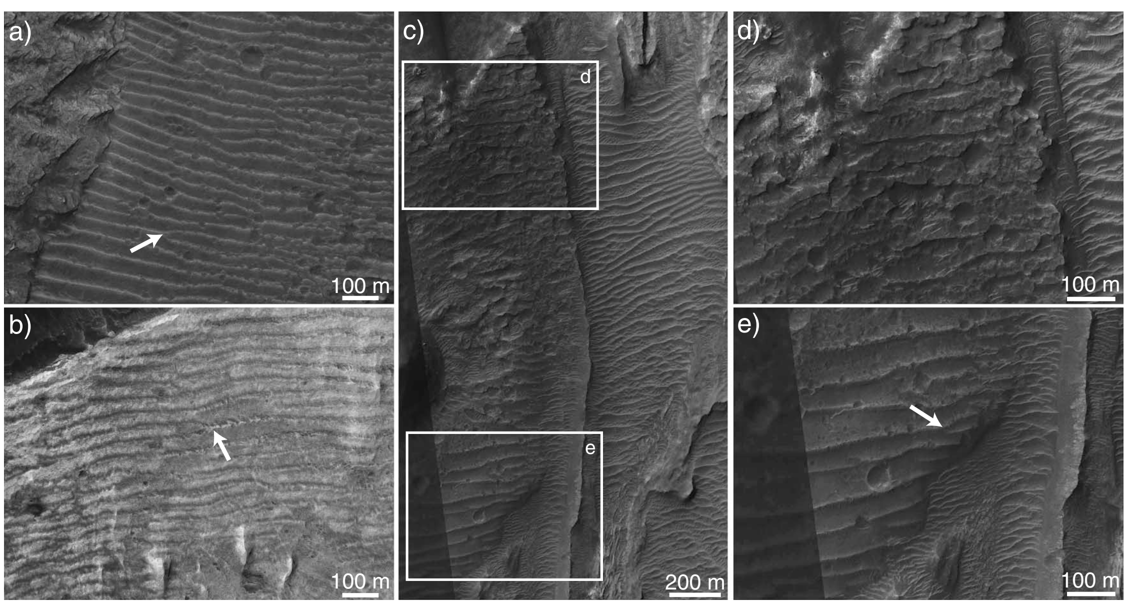


**Figure 2.** Examples of preserved dune bedforms. (a) Bedforms in a unit along the southern margin of Mount Sharp; retention of craters and a cross-cutting fracture (northwest portion) indicate the unit is lithified. (b) Bedforms on an exposed surface in Mount Sharp near the Lower formation-Upper formation contact. (c) Example of preserved bedforms undergoing erosion and transitioning to washboard morphology. (d) Close-up of washboard that results from preferential preservation of interdune materials by erosion of (e) crests in preserved bedforms. White arrows indicate bifurcation. North is up in all images. See Table SA1 for HiRISE image IDs.

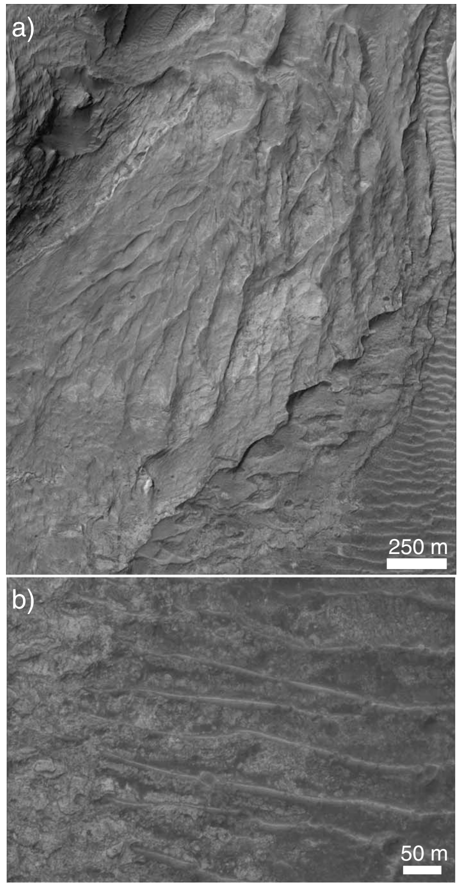


**Figure 3.** Preserved bedforms overlain by fan deposits along the SW margin of Mount Sharp. (a) Fan deposit derived from incision of the Lower formation showing inverted topography; (b) close-up of lighter-toned sediments associated with the fan in Figure 3a that overlie darker preserved bedforms and are undergoing erosion. Note the bifurcation and preserved craters in the bedforms. North is up in all images. HiRISE image ESP025012_1745.

location indicate the presence of a hydrated phase but are too noisy to allow more specific phase identifications; spectra of equivalent strata in other locations of the Lower formation indicate the presence of hydrated sulfates [*Milliken et al*., 2010]. Another example of this style of stratification can be observed in the wall of a large canyon in the western portion of the Lower formation (Figure 1b). Here we interpret a ~50–75 m thick unit to exhibit ~25 m thick subcritically climbing dune sets with foresets that have an apparent dip of approximately 30°—this crest-perpendicular or slightly oblique cross section can be used to estimate the true direction of dune migration at ~150° from North. At the same location, beds in overlying and underlying units do not exhibit such steep apparent dips and may represent either oblique cross sections or preservation of the lower, downlapping portion of the dune set or low-angle sand sheet cross stratification [*Kocurek and Nielson*, 1986].

The style of stratification shown in Figure 1 is consistent with an eolian origin and exhibits relatively regular set thicknesses, which is generated by regular crest spacing and trough elevation of migrating dunes. Though regular set thickness may arise with any type of dune accumulation—wet, damp, or dry—in many terrestrial environments where this is observed, interdune areas tend to be damp or wet (e.g., Entrada Sandstone; rare areas of the Navajo Sandstone) [*Kocurek*, 1981]. In the case of wet or damp conditions, accumulation of eolian sediment is driven by a relative rise in the groundwater table that promotes early diagenesis, cementation, and thus limits the depth of scour down to the capillary fringe. Sandstones have been observed elsewhere on Mars by the *Opportunity* rover in Meridiani Planum, where ~80–100 m of section was interpreted as a dune-playa environment that experienced intermittent flooding by rising groundwater [*Grotzinger et al*., 2005; *Edgar*, 2013]. We cannot observe from orbit the small-scale structures required to determine if these sandstones in Mount Sharp formed in a wet, damp, or dry system and whether or not groundwater ever breached the surface, but postdepositional circulation of pore fluids in the Lower formation is supported by the presence of filled fractures that are indicative of mineralization-induced strengthening [*Anderson and Bell*, 2010] (see examples in Figure SA2).

Another set of observations consistent with the presence of sandstones in Gale Crater is the remarkable and widespread occurrence of lithified bedforms in which the original surface topography of the dunes is either wholly or partially preserved (Figure 2, additional examples in Figures SA3–SA5 in the supporting information). These surfaces are characterized by straight-crested dunes that exhibit crest line defect interactions and bifurcations. With apparent wavelengths of ~40–60 m and heights of ~1–4 m, these Martian features are similar in size to the largest wind ripples found on Earth as reported by *Milana* [2009]. The bedforms are lithified, as indicated by their retention of later impact craters, the presence of erosional scarps at the edges of bedding planes, and occurrence of cross-cutting fractures (Figures 2 and SA3). *Montgomery et al*. [2012] discussed the potential for features with similar morphology to be erosional features they termed periodic bedrock ridges (PBRs). Unlike key characteristics of the PBRs shown in that study, the features presented here do not cut across local stratigraphic contacts or bedding, appear to be concordant with bedding plane surfaces, are restricted to

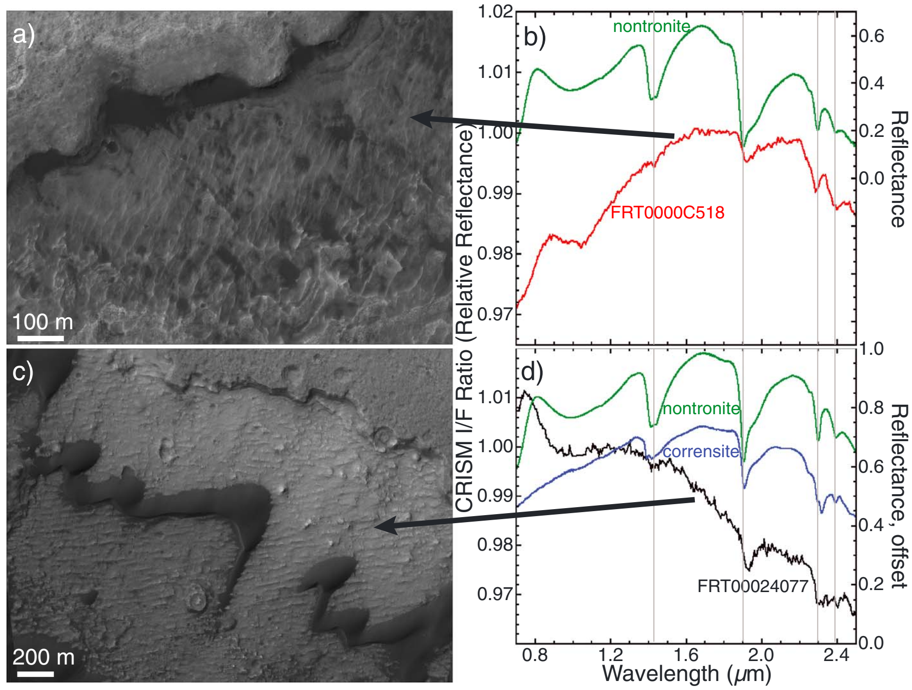


**Figure 4.** Preserved bedforms associated with clay minerals. (a) Possible bedforms in the Lower formation along the northern portion of Mount Sharp (see Figure 1); (b) CRISM spectral ratios from a full resolution targeted (FRT) (~18 m/pixel) observation averaged over the geologic unit in Figure 4a indicated by the arrow, consistent with the presence of Fe-bearing clay such as nontronite; (c) Preserved bedforms exposed on the crater floor along the western margin of Mount Sharp; (d) CRISM spectral ratio (from ~18 m/pixel FRT; location shown in Figure SA6b) indicating that signatures in the geologic unit indicated by the arrow are consistent with Fe/Mg clays such as smectite or mixed-layer chlorite-smectite (e.g., corrensite). See supporting information for spectral-processing methods and Table SA1 for HiRISE image IDs. North is up in all images.

certain stratigraphic units, and appear to be linear over longer distances (commonly hundreds of meters) before bifurcating or terminating. Importantly, the bedform features in Gale also exhibit internal stratification consistent with deposition by bedform migration, not erosion (see Figure SA5). One previously noted example of these features in Gale is exposed along an eroded bedding plane near the top of the Lower formation (Figure 2b) [*Malin et al*., 2010], and CRISM data have shown that similar strata in the upper portion of the Lower formation contain monohydrated and polyhydrated sulfate salts [*Milliken et al*., 2010].

Examples of preserved bedforms are common near the base of Mount Sharp in units that superpose the lowermost strata of the Lower formation and in units exposed in the crater floor (Figures 2–4 and SA3). Preserved bedforms in one location along the southern margin of Mount Sharp underlie strata produced by fluvial incision of the Lower formation, indicating these bedforms predate the formation of the fan deposits (Figures 3 and SA4). If fluvial incision of the Lower formation predates deposition of the Upper formation, as suggested by lack of channels in the Upper formation, then this would place a Late Noachian-Early Hesperian age constraint on these preserved bedforms. Some units along the base of Mount Sharp also exhibit a "washboard" erosional style suggestive of cemented and partially eroded bedforms [*Anderson and Bell*, 2010]. Examples of this morphology along the southern margin of the mound transition into wholly preserved bedforms, providing evidence that this morphology is produced by erosion of these preserved dunes (Figures 2 and SA5). From this transition we interpret the raised, flat-topped portions of the washboard to result from preservation of interdune areas or cemented upper bounding surfaces accompanied by preferential erosion of dune crests, a characteristic that has been recognized in terrestrial examples of preserved bedforms where preferential sedimentation and cementation in interdune regions leads to differential erosion and inverted dune topography [*Fryberger*, 1986].

There are at least three occurrences of preserved bedforms associated with clay minerals. The first occurs in a topographic trough along the northern edge of the mound and corresponds to the strongest spectral signatures of Fe-smectite in Gale [*Milliken et al*., 2010; *Thomson et al*., 2011] (Figures 4a and 4b). The presence of NE-SW trending linear ridges has been noted previously in this location, where it was suggested that these might represent linear dunes [*Anderson and Bell*, 2010], but the textures are not as well developed as the other examples presented here. If these are indeed remnants of eroded bedforms, then they may represent preserved dunes that were partially reworked during flooding and burial—processes well known from eolian strata on Earth [*Fryberger*, 1986; *Eschner and Kocurek*, 1988; *Benan and Kocurek*, 2000; *Glennie and Buller*, 1983]. Alternatively, they may be poorly expressed because of partial coverage and incomplete erosion of overlying clay-bearing beds. An example with better-preserved bedforms is found on the crater floor to the west of the mound (Figures 4c, 4d, and SA6). The relief of these bedforms is muted due either to erosion of the dunes themselves or thicker infill/less erosion in the interdune regions. CRISM spectral data were processed similar to methods described in *Milliken et al*. [2010] (see supporting information for details) and support the presence of Fe/Mg smectite or mixed-layer chlorite/smectite in these strata. A third location along the southern margin of Mount Sharp also exhibits bedforms associated with hydrated minerals, and though the spectral signatures are relatively weak, they are consistent with clays and possibly an additional hydrated phase (Figures SA7 and SA8).

## 3. Discussion

Lithified eolian bedforms from ancient sand seas are known in the terrestrial rock record, but they are exceedingly rare because of the unique conditions required for vertical sediment accumulation to outpace lateral erosion during bedform migration. The dunes must be either quickly stabilized and later buried or rapidly buried in a (largely) nondestructive manner in order for the original surface topography to be preserved instead of eroded. On Earth, the latter is often accomplished by rapid transgressions that flood the dune field, with examples known from the Entrada sandstone in New Mexico, U.S., and the Weissliegend sandstone in Europe [*Fryberger*, 1986; *Eschner and Kocurek*, 1988; *Benan and Kocurek*, 2000; *Glennie and Buller*, 1983]. Terrestrial examples of dunes preserved by lava floods are also known [*Mountney et al*., 1999; *Jerram et al*., 2000], and though we cannot rule this out for Gale Crater, there are currently no indications that any of the strata in Gale represent lava flows. Instead, dune preservation in a closed basin like Gale may have been promoted by a rapidly rising groundwater table that flooded the surface, followed by rapid sedimentation and cementation of bedforms by authigenic mineral phases. Rapid sedimentation and burial is also consistent with the occurrence of bedforms preserved under fan deposits along lower Mount Sharp (examples in Figures 3, SA4, SA5, SA7, and SA8).

Where preserved dunes are associated with clays, it is less clear if the clays are in the dunes themselves or in overlying beds undergoing denudation and revealing the underlying dune topography. The latter would be consistent with preservation of the dunes through burial by fine-grained material and explain why the morphology of the clay-bearing material in Figure 4a has a diffuse appearance; only thin remnants of clay beds remain. Alternatively, the clays may exist as cements within the preserved bedforms, either as detritus from postdepositional infilling or as a result of direct precipitation from pore fluids. Authigenic clay cements are extremely common components of sandstones of all age, across a wide range of depositional environments. Exhaustive petrographic studies have shown that over 90% of terrestrial sandstones contain authigenic clays as pore lining or filling cements, including smectite and chlorite [*Wilson and Pittman*, 1977; *Ajdukiewicz et al*., 2010]. Indeed, clays detected by Curiosity in mudstones located several kilometers from lower Mount Sharp have been interpreted as authigenic products [*Vaniman et al*., 2013; *Grotzinger et al*., 2013], and we hypothesize that the clay minerals widely observed in the Lower formation of Mount Sharp may also be authigenic in origin, precipitated from diagenetic pore fluids or infiltrating surface waters that interacted with basaltic sand. In one scenario, fluvial incision of the Lower formation could have promoted dissolution of the highly soluble Mg sulfates [*Milliken et al*., 2010], forming Mg-rich fluids that flooded dune fields along the base of Mount Sharp and that now underlie fan deposits such as in Figure 3. Such fluids could have precipitated Mg-bearing clay minerals in the dune pore space, promoting rapid lithification.

## 4. Conclusions

The ongoing Curiosity rover mission will be able to test hypotheses of authigenic clay formation in eolian sandstones as it approaches Mount Sharp by examining in detail any differences in mineralogy, lithology, and stratal geometry between proposed dune and interdune regions. If clay-bearing material is found to occur as distinct beds that overlie, are finer-grained than, and onlap the dunes in the interdune regions, then the clays could be detrital or authigenic. The preservation of bedforms would then be consistent with rapid burial by fine-grained sediment, though this does not preclude the possibility that they may be cemented by clay, sulfate, or hematite, all of which have been observed in the Lower formation [*Milliken et al.*, 2010; *Thomson et al.*, 2011]. Alternatively, if rover observations show that the clays reside within the sandstones, then it is difficult to imagine a wind regime that would allow accumulation of such a bimodal sediment size distribution. As is common in terrestrial sandstones, these clays could be authigenic in origin and represent pore-lining or filling cements. If authigenic clays in Mount Sharp are confirmed by Curiosity, it would provide important information on local water-rock interactions and help to bridge the gap between orbital predictions and surface observations, allowing a more comprehensive assessment of the potential for the preservation of organic chemical compounds within the entirety of Gale Crater.

**Acknowledgments**
REM was supported for this work in part by NASA MDAP grant NNX12A063G. We thank John Grotzinger and Dave Rubin for insightful comments during the preparation of this paper. We also thank David Loope and Lauren Edgar for thoughtful reviews that improved the manuscript.

The Editor thanks David Loope and an anonymous reviewer for their assistance in evaluating this paper.

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