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Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater

R. E. Milliken,[1] J. P. Grotzinger,[2] and B. J. Thomson[3]

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[1] A kilometers-thick sedimentary sequence in Gale Crater exhibits stratigraphic changes in lithology that are consistent with transitions in aqueous and climatic conditions purported to be global in scale. The sequence is divided into two formations, where the Lower formation exhibits a net transition in mineralogy from clay/sulfate to sulfate/oxide assemblages and is separated from the overlying Upper formation by an erosional unconformity. Superposition and crater counts suggest strata in the Lower formation lie along the Noachian-Hesperian time-stratigraphic boundary, whereas beds in the Upper formation, which lack signatures indicative of clay minerals or sulfates, are thinner, more regularly spaced, and clearly younger. The observed stratigraphic trends are consistent with the rocks at Gale Crater recording a global transition from a climate favorable to clay mineral formation to one more favorable to forming sulfates and other salts. **Citation:** Milliken, R. E., J. P. Grotzinger, and B. J. Thomson (2010), Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater, *Geophys. Res. Lett.*, *37*, L04201, doi:10.1029/2009GL041870.

1. Introduction

[2] Our understanding of the evolution of Earth's very ancient climate derives from detailed examination of the mineralogic, textural, and geochemical signatures preserved in the sedimentary rock record. These insights have been obtained through analysis of globally-distributed strata and through identification and integration of those stratigraphic sections that best characterize the changes in Earth's environment. These "reference" sections also provide the stratigraphic tie points that serve as benchmarks by which all ancient terrestrial processes are compared in time. It is reasonable to assume that the climatic evolution of Mars is also recorded in its stratigraphic record, and constructing a relative global chronology that reveals secular change in surface environments will similarly require identification of that planet's key reference sections. Past work has shown that sedimentary rocks exist on Mars [e.g., *Malin and Edgett*, 2000] and exhibit diverse attributes at a range of spatial scales [e.g., *Malin and Edgett*, 2000, 2003; *Grotzinger et al.,* 2006; *Dromart et al*., 2007; *Lewis et al.,* 2008], but it is less clear how many localities preserve stratigraphic successions that contain a broad range of petrologic attributes and which of these sections record consistent evolutionary chronologies.

[3] Recent interpretations of data collected by the Mars Express and Mars Reconnaissance Orbiter (MRO) spacecraft have confirmed the role of water on the surface and much recent work has focused on the presence of hydrous minerals. The apparent spatial and interpreted temporal distribution of such minerals has led to the hypothesis that the planet evolved from a wetter climate conducive to clay mineral formation under alkaline conditions to a water-limited climate that favored precipitation of sulfates and other salts under more acidic conditions at ca. 3.8–3.6 Ga [*Bibring et al*., 2006; *Murchie et al.,* 2009]. It is also proposed that Mars has been in a dry and oxidative state for the past several billion years, one in which eolian processes and surface-ice interactions may have dominated, and that those processes may have been strongly influenced by orbital forcing [*Head et al.,* 2003; *Lewis et al*., 2008]. Previous studies have shown that clay mineral and sulfate-bearing rocks commonly occur in spatially isolated deposits with different crater-count ages [*Bibring et al.,* 2006] but for which stratigraphic relationships are unclear. However, formation of alteration minerals may depend on spatially dependent variables such as precipitation or protolith composition, thus observing these mineralogic changes through a clear stratigraphic succession is an important independent test of this model. Here we present evidence that a ~5 km thick sedimentary sequence in Gale Crater captures an upward transition from clay mineral to sulfate/Fe-oxide-bearing rocks and thus is a potential reference section for at least part of the proposed global environmental evolution of early Mars.

2. Background

[4] Gale Crater is a ~155 km diameter Noachian-age crater on Mars located along the geomorphic and topographic boundary that separates the ancient heavily-cratered southern highlands from the younger and topographically smoother northern lowlands. The crater contains a remarkably thick ~5 km sequence of stratified rocks that form a mound whose maximum elevation is similar to that of the southern crater rim but is up to several kilometers higher than the degraded northern rim (Figure 1a). The mound exhibits no unambiguous volcanic landforms (e.g., lava flows, vents, cones) and thus the rocks are considered to be sedimentary in origin [*Malin and Edgett*, 2000]. Other researchers have interpreted the strata as being volcanic ash, lacustrine [*Cabrol et al*., 1999], eolian, spring mound [*Rossi et al*., 2008], or ancient polar deposits [*Schultz and Lutz*, 1988].

[1]Jet Propulsion Laboratory, Pasadena, California, USA.
[2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.
[3]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.

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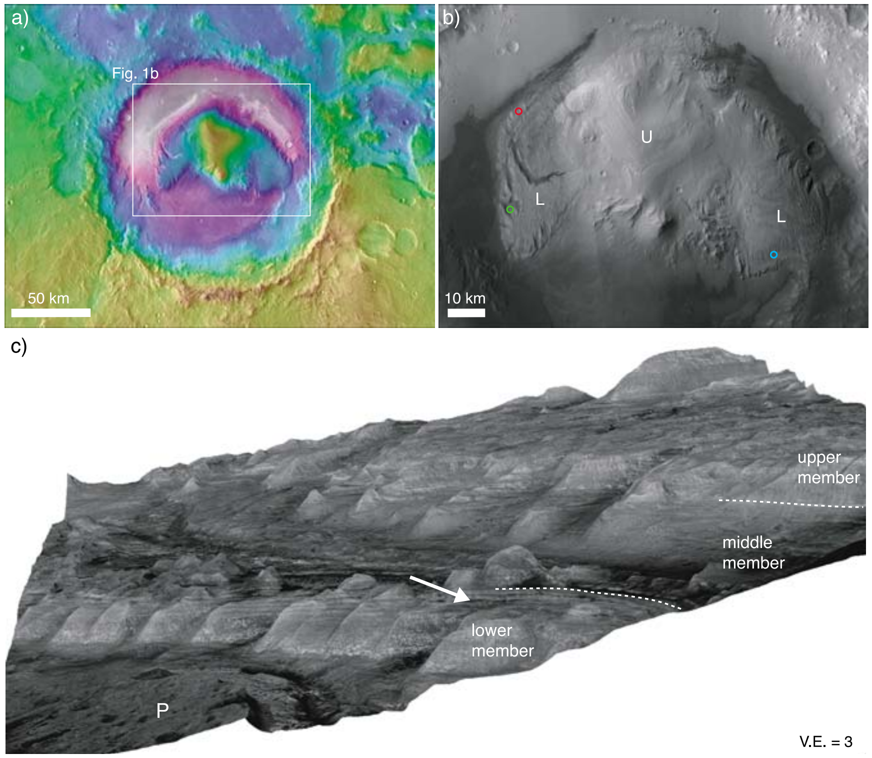

Figure 1. Orbital views of Gale Crater. (a) MOLA topography overlain on a daytime infrared mosaic. (b) CTX mosaic showing morphologic differences between the Upper (U) and Lower (L) formations. Colored red, green, and blue circles correspond to locations of Figures 2c–2e, respectively. (c) Perspective view to the southeast from HiRISE DTM highlighting morphologic differences in the 3 members of the Lower formation and the onlapping pyroxene-bearing crater floor unit (P). White arrow marks the location of nontronite-bearing beds at top of lower member.

[5] The distance between the present edges of the mound and the crater wall is commonly on the order of ~10–30 km, and the strata exposed in the lower portion of the mound exhibit nearly horizontal bedding and do not show signs of tapering in thickness towards their current limit. These characteristics suggest the strata were once much more laterally extensive and it is possible that the entire crater was once filled and buried with sediment [*Malin and Edgett*, 2000]. Whether completely or only partially filled, Gale Crater is one of a family of ancient impact basins in which sediments were deposited, lithified, and then eroded such that only a fraction of the original material remains in the crater. Other examples include the craters Henry, Terby, Pollack and craters in northern Sinus Meridiani [*Malin and Edgett*, 2000]. In this context, understanding the geologic history recorded in Gale strata can provide insight into general processes and environmental conditions that may have been regional or global in scale.

3. Results

[6] Visible images acquired by the MRO High Resolution Imaging Science Experiment (HiRISE; 25 cm/pixel) and Context Camera (CTX; 6 m/pixel) were integrated with digital terrain models (DTMs) derived from visible images (see auxiliary material) and visible-near infrared reflectance spectra acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; ~18–36 m/pixel) to examine variations in lithology (mineralogy) with stratigraphic position in the Gale Crater mound.[1] These images were also used to trace individual beds and geologic contacts across the mound, providing additional insight into stratigraphic relationships over long distances. HiRISE DTMs have a vertical accuracy of <1 m and were used to make strike, dip, and bed thickness measurements using techniques similar to those of *Lewis et al.* [2008] and *Lewis* [2009] (see auxiliary material). The boundaries for individual beds were defined based on changes in albedo, surface texture, and/or erosional patterns, though whether such changes represent primary or secondary (diagenetic) horizons remains unknown. Bed thicknesses range from <1 m up to ~18 m, though beds at the thicker end are likely composed of numerous thinner beds that are either amalgamated or cannot be distinguished by changes in albedo or surface texture, and beds at the meter scale are possibly composed of thinner beds not resolved in available data. Therefore, many more depositional events are likely recorded in the stratigraphic section at Gale than there are beds observed in existing images.

[7] The mound in Gale Crater can be divided into two formations based on visible images (Figure 1). The Lower formation is composed of parallel beds that dip gently to the northwest at 2–4° and vary in thickness, albedo, and surface texture, whereas strata in the Upper formation appear relatively homogeneous, dip more steeply towards the north-northeast, and have fewer impact craters (Figure 2a). The

[1]Auxillary materials are available in the HTML. doi:10.1029/2009GL041870.

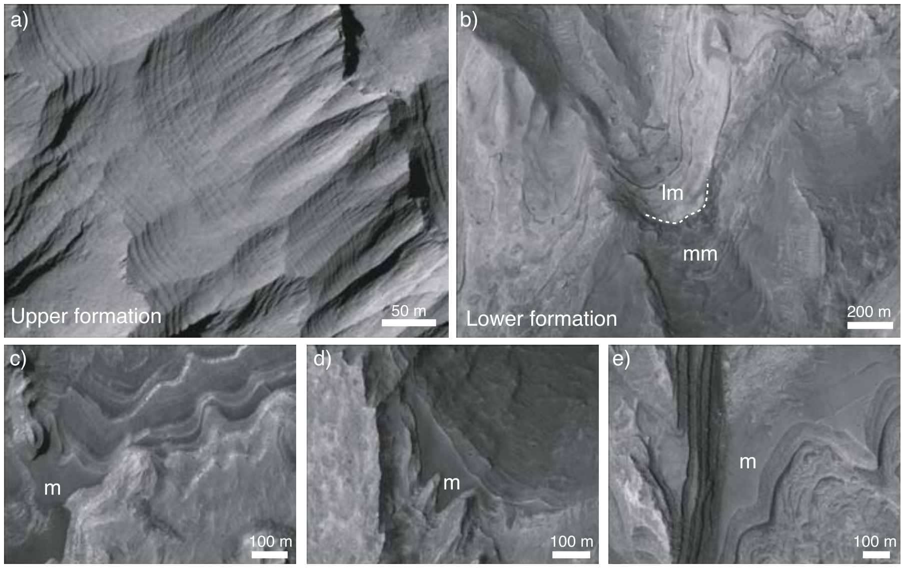

Figure 2. HiRISE images of strata in the Gale Crater mound. (a) Beds in the Upper formation that, in contrast to beds in the Lower formation, exhibit a regular thickness of several meters. (b) Contact between lower (lm) and middle (mm) members of the Lower formation and corresponding change in albedo. (c, d, e) Examples of the dark-toned marker bed (m) at the boundary between the middle and upper members of the Lower formation. Locations correspond to red, green, and blue circles in Figure 1b, respectively.

contact between the Lower and Upper formations is largely obscured by debris, but changes in bedding orientation and topography imply they are separated by an erosional unconformity. Although the high degree of differential erosion makes it difficult to determine ages of the two formations via crater counts, the measured crater retention age of the entire mound yields an apparent age near the Late Hesperian-Early Amazonian boundary. However, the presence of numerous exhumed craters in some horizons attests to a more prolonged history of burial and exposure, suggesting this young age represents an exposure age or resurfacing age rather than a depositional age. Superposition shows that deposits on the floor of Gale Crater onlap and thus postdate the beds of the Lower formation. The crater retention age of the floor units provide a minimum age of Early Hesperian, whereas an upper age limit of Late Noachian was determined by examining the crater population superposed on the degraded ejecta of Gale Crater. Thus the depositional age of the mound is loosely constrained to Late Noachian/Early Hesperian, though the unconformity between the Lower and Upper formations represents an unknown amount of time and the Upper formation could be much younger in age, potentially Amazonian.

[8] The Lower formation was further divided into three members for which a boundary between the lower and middle member was designated near the base of the northwest portion of the mound where a distinct transition from light to darker-toned strata is observed in grayscale images (Figure 2b). Approximately 150 meters higher in the section, the top of a distinctive marker bed characterized by a dark, smooth surface and overlain by brighter, fractured beds is used to define the boundary between middle and upper members of the Lower formation (Figures 2c–2e). This marker bed is most prominent in the northwest section of the mound but is also observed in the canyons on the west side of the mound and in outcrops on the southeast portion of the mound (Figure 2e). This boundary also coincides with a transition from darker-toned rocks back to lighter-toned rocks, although changes in outcrop albedo are muted by surficial debris in some locations.

[9] The member boundaries were chosen solely on morphologic characteristics, but analysis of CRISM data reveal that they also coincide with changes in mineral composition. Spectral ratios (see auxiliary material) for the Lower formation show abundant hydration signatures, characterized by the presence of sulfates in the lower member, a transition to clay mineral-bearing rock at the lower-middle member boundary, a gradation to sulfate-clay mixtures in the middle member, and a progression to sulfate-bearing rocks in the upper member (Figures 3 and 4). In contrast, spectra for the Upper formation lack absorptions indicative of hydrated minerals and are similar to the ubiquitous Martian dust. The clay mineral-bearing strata occur as thin, recessive beds, whereas the sulfate-bearing rocks that bound them on either side erode to form cliffs (Figure 1c). Clay mineral signatures are most consistent with Fe-smectite (nontronite; Figure 3b) and are confined to several thin beds immediately below the lower-middle member contact (Figure 4), particularly where the strata are eroded along bedding planes such that their areal exposure is greater than their thickness. Spectra for strata in the middle member indicate the presence of both clay and sulfate, though whether these rocks are sulfate-cemented clays or alternating thin beds of clay minerals and sulfate cannot be determined at the spatial resolution of CRISM. Similar trends in mineralogy and morphology are observed in a stratigraphically equivalent section exposed in the large canyon that incises the Lower formation on the west side of the mound (Figure 3a), demonstrating that these beds are laterally continuous over at least several tens of kilometers.

[10] Spectra of both mono- and polyhydrated sulfates are observed in the Lower formation, where the lack of strong

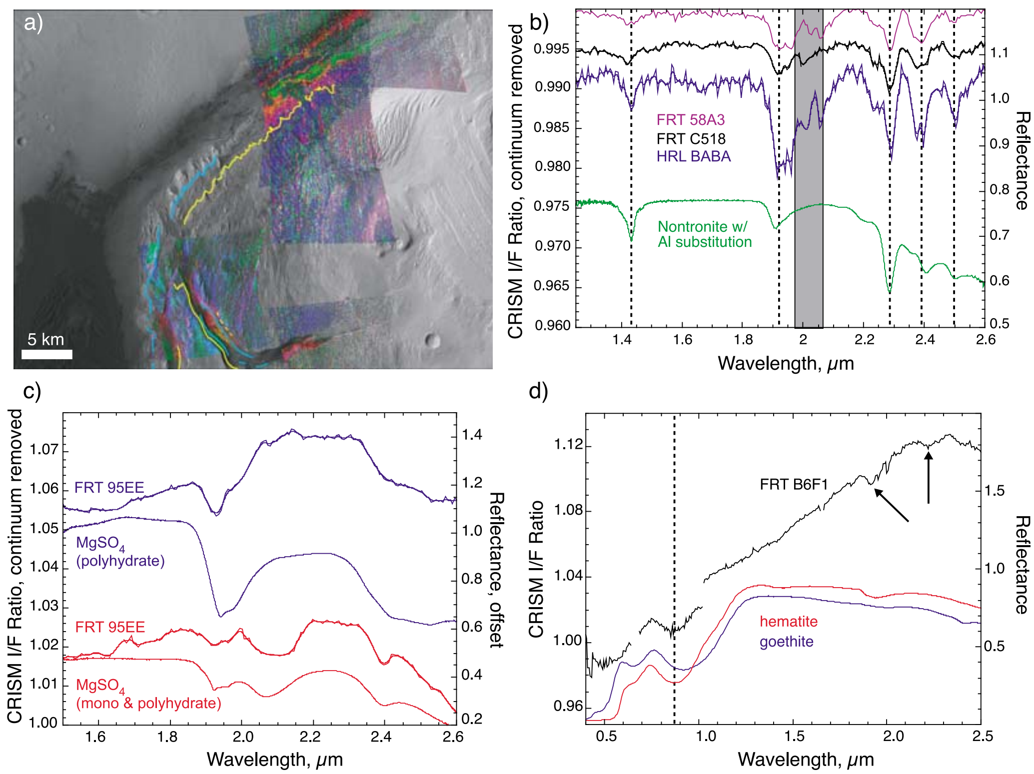

Figure 3. Mineralogy of Gale Crater. (a) CRISM RGB mineral parameter maps (red = Fe-minerals, green = Fe/Mg-clay minerals, blue = sulfates) overlain on CTX mosaic. Bright red regions correspond to olivine-bearing dunes, green regions contain nontronite, and dark blue regions contain sulfates. Orange and magenta regions contain sulfates and clay minerals in variable proportions. Cyan and yellow lines mark the lower-middle and middle-upper member boundaries of the Lower formation and are based on tracing beds in visible images. (b) CRISM ratio spectra from 3 different observations of the same clay-bearing beds compared to a laboratory spectrum of nontronite. The weak absorption near 2.2 μm suggests some Al is present in a separate clay mineral or in octahedral sites of the nontronite. (c) CRISM ratio spectra of mono- and poly-hydrated sulfates compared to laboratory spectra. (d) CRISM ratio spectra with features indicative of hydrated phases (arrows) and crystalline Fe-oxides (dashed line).

ferrous absorptions in the former suggest it is likely the Mg-variety kieserite ($MgSO_4 \cdot 1H_2O$). Similarly, spectra of the polyhydrated sulfates are inconsistent with Ca varieties and lack strong Fe absorptions, suggesting they are likely Mg-sulfates (Figure 3c). The strongest sulfate signatures occur in the upper portion of the middle member, throughout the upper member, and in detritus sourced from these strata that has accumulated on canyon floors and other topographic lows. Crystalline ferric oxide (hematite) is also observed in some of the sulfate layers (Figure 3d), most prominently in remnant outcrops on the north side of the mound that have been scoured by surrounding olivine-rich sand dunes. The units on the floor of the crater, including those that onlap the lower strata of the mound, exhibit spectral signatures consistent with the presence of pyroxene and might be basaltic sandstones.

4. Discussion

[11] As independent proxies, the morphology and mineralogy point toward distinct lithologic changes at similar horizons in the Gale mound stratigraphy, implying changes in environmental conditions and/or sediment source region. Clay mineral-bearing strata decrease in abundance upward throughout the Lower formation, thus recording the secular evolution from clay mineral/clay-sulfate assemblages to net sulfate assemblages. Furthermore, these rocks are unconformably overlain by strata of the Upper formation that lack evidence of aqueous interaction and exhibit a regular thickness of several meters (Figures 2a and 4) [*Lewis*, 2009]. These characteristics are similar to strata observed elsewhere on Mars interpreted to result from orbital forcing [*Lewis et al.,* 2008], though quasi-periodicity related to the intrinsic process of sediment accumulation itself cannot be ruled out. Thermal inertia values of the Upper formation suggest large portions are likely covered with fine-grained unconsolidated material, whereas values for the Lower formation are consistent with bedrock [*Pelkey and Jakosky*, 2002; *Pelkey et al*., 2004]. The Lower formation also has been incised by several large canyons, whereas the Upper formation has not and lacks hydrated mineral signatures. This suggests the possibility that the Upper formation is not only covered in dust today, but that it may have originally been formed by largely non-aqueous processes, including fallout and lithification of suspended dust in addition to eolian bedload transport of coarser sediments. This would be consistent with the general decrease of fluvial erosion of the Martian surface through time [e.g., *Carr*, 1996; *Fassett and Head*, 2008].

[12] Ultimately, the origin of the enormous amount of material in Gale remains unknown. Therefore, whether compositional changes in the rocks represent variability in

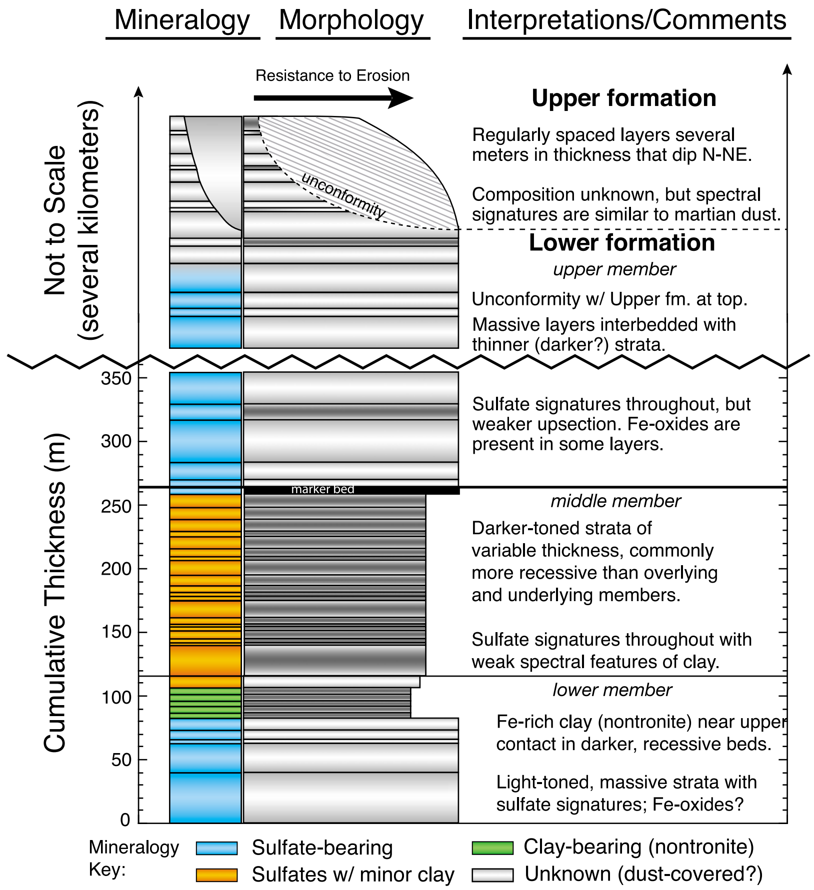

Figure 4. Interpreted stratigraphic column for a section of the Gale Crater mound. Where marked, bed thicknesses are measured from HiRISE DTMs. Mineralogical interpretations are based on CRISM data, though not all individual beds observed in HiRISE images are resolved in CRISM images. A group of thin (<7 m) recessive beds in the lower member contains clays (green), whereas the middle member exhibits sulfate and very weak clay signatures (orange). Sulfate-bearing beds (blue) are generally thicker than clay-bearing beds and are found throughout the upper member. Gray and white beds in the morphology column are qualitative indicators of general changes in albedo.

local aqueous geochemistry or significant changes in sediment source region is unclear, although nontronite or sulfate deposits have not yet been identified directly adjacent to Gale. Some of the sulfate-bearing beds exhibit weak pyroxene signatures, suggesting they may be evaporites with a siliciclastic component or sulfate-cemented eolian deposits. Many terrestrial evaporite deposits also contain detritus with a terrigenous origin, making the origin of clay minerals at Gale ambiguous as well. If detrital, changes in sediment composition at Gale would represent evolution of the environmental conditions at the source region(s) rather than within the crater. Whether the clay minerals and sulfates are detrital or authigenic, the implication is the same: the transition from a weathering environment conducive to clay mineral formation to one favorable to sulfates and ultimately anhydrous minerals would still record a regional to global scale transition [*Bibring et al.*, 2006].

5. Conclusions

[13] The general transition from clay minerals to sulfates/oxides to unaltered rocks in Gale Crater, the approximate Noachian-Hesperian age of the Lower formation, and the apparent spatial-temporal segregation of clay mineral and sulfate-bearing terrains on a global scale are all consistent with the major mineralogic and climatic changes proposed by *Bibring et al*. [2006]. In this scenario, the Lower formation captures the transition from conditions favorable to clay mineral formation to those favorable to sulfate formation along the Noachian-Hesperian (Phyllosian-Theiikian of *Bibring et al*. [2006]) boundary, although Al- or Fe-sulfates indicative of highly acidic conditions have not yet been identified in Gale Crater. We interpret the younger Upper formation to represent a drier climate, possibly during the Late Hesperian-Amazonian (Siderikian). These transitions may represent the progressive ‘drying out’ of Mars from early clement conditions, to water-limited acidic and oxidizing conditions, and ultimately to the cold, dry climate of today in a single stratigraphic sequence.

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J. P. Grotzinger, Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA.

R. E. Milliken, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA. (ralph.milliken@jpl.nasa.gov)

B. J. Thomson, Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.