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Hypotheses for the origin of fine-grained sedimentary rocks at Santa Maria crater, Meridiani Planum

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ABSTRACT

En route to Endeavour crater, the Mars Exploration Rover *Opportunity* embarked on a short but significant campaign at Santa Maria crater during sols 2450–2551. Santa Maria crater is a relatively young impact crater, approximately 100 m in diameter and 11–17 m deep. *Opportunity* performed detailed analyses on several ejecta blocks and completed an extensive imaging campaign around the crater. Many of the ejecta blocks are composed of sandstone with abundant wind ripple laminations suggestive of eolian deposition. However, other ejecta blocks are massive, fine-grained, and exhibit a nodular texture. These rocks are interpreted to be the first rocks of a grain size smaller than the Microscopic Imager can resolve, and may represent the first mudstones observed by the rover. Several depositional environments are considered for the origin of the fine-grained rocks, and the observations are best fit by a transient evaporitic lake. If the inferred mudstones were deposited in a lacustrine setting, then surface water may have been present in a broader range of surface environments than previously documented at Meridiani Planum.

1. Introduction

For the past nine years, the Mars rover *Opportunity* has been exploring sedimentary rocks exposed in impact craters at Meridiani Planum (e.g., Squyres et al., 2006a,b, 2009; Arvidson et al., 2011). Key scientific investigations were carried out at Eagle, Endurance, Erebus, Victoria and Santa Maria craters (Fig. 1). Of particular interest is the examination of rocks formed in aqueous environments, because of their implications for the potential habitability of ancient martian surface environments. Substantial evidence for aqueous activity was discovered at Eagle, Endurance, and Erebus craters (Squyres et al., 2004; Clark et al., 2005; Grotzinger et al., 2005, 2006; McLennan et al., 2005; Metz et al., 2009). The sedimentary rocks exposed at these craters—collectively named the Burns formation—are interpreted to record a dry to wet eolian depositional system (Grotzinger et al., 2005, 2006; Metz et al., 2009). Bedrock outcrops at Victoria crater, however, reveal eolian environments with no evidence for water-lain sediments (Edgar et al., 2012). At each of these craters, sediments are interpreted to have been derived from reworked playa mudstones, with pore-water fluids that were ultimately sourced from acid-sulfate weathering of basalt (McLennan et al., 2005; McLennan and Grotzinger, 2008). At each of these sites, regardless of primary depositional facies, there is evidence for diagenesis involving the formation of hematite concretions, precipitation of crystals now represented by pseudomorphs, and recrystallization. Each new outcrop exposure allows the testing and refinement of models for sediment production, transport, deposition and erosion. Significantly, only fine-to-medium-grained sandstones have been observed in the course of detailed examination of these outcrops. More finely grained rocks could provide substantial additional support for the hypothesis of a lacustrine depositional environment, which is inferred to have been the source for at least some of the Burns formation.

After leaving Victoria crater, *Opportunity* set out on a three-year trek to reach Endeavour crater, but the rover made several stops along the way. One of those stops was at Santa Maria crater, which is located ~7 km southeast of Victoria crater and exposes a lower stratigraphic level than had been previously explored. Observations of ejecta blocks at Santa Maria crater reveal primarily eolian stratification, in addition to a new facies that is characterized by massive, and sometimes nodular, fine-grained sedimentary rocks that we interpret here as potential mudstones or duststones.

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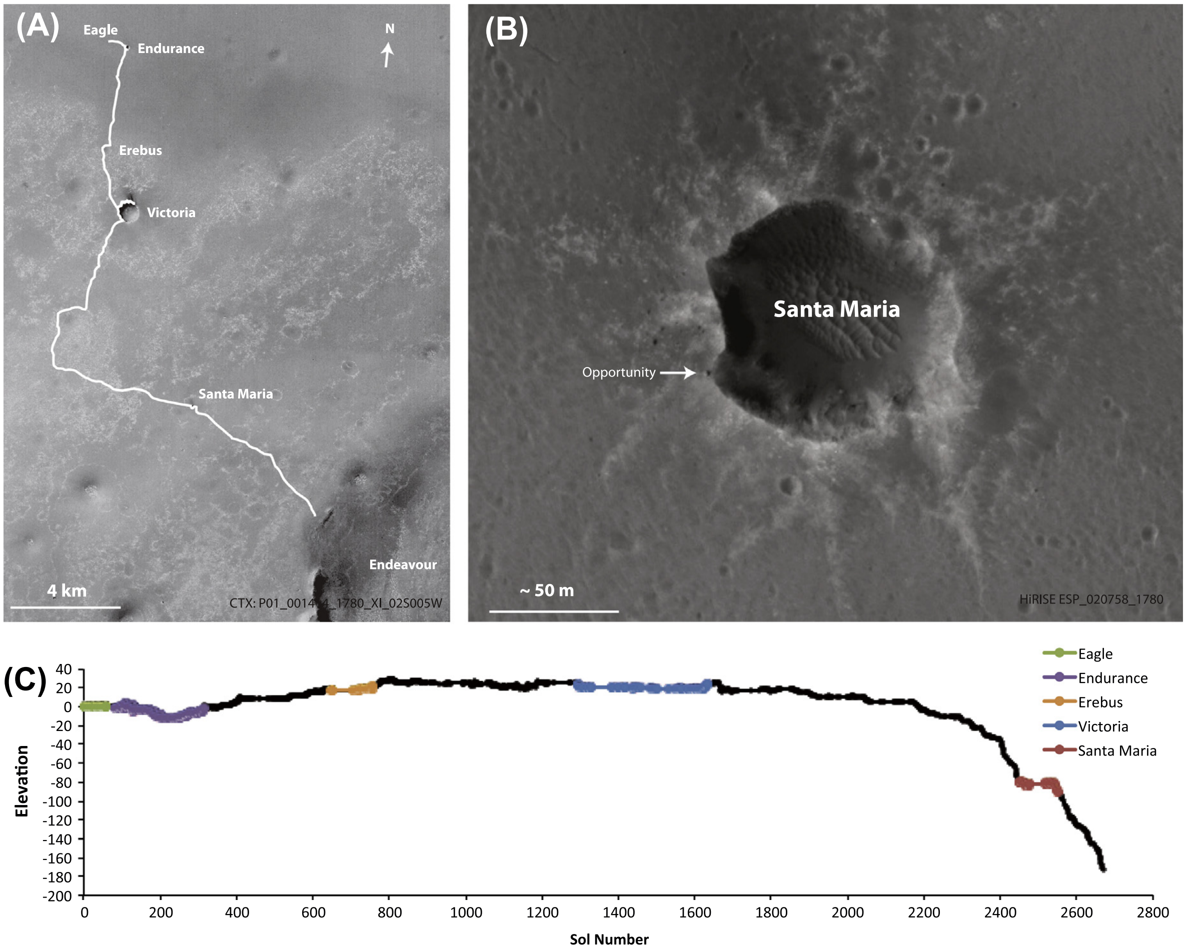

Fig. 1. (A) Rover traverse map as of sol 2670 plotted on Context Imager (CTX) image P01_001414_1780_XI_02S005W. Santa Maria crater is located about 7 km southeast of Victoria crater. (B) Santa Maria crater in HiRISE image ESP_020758_1780. The rover approached the crater on the western rim, and drove around the rim to the south, where it observed target Ruiz Garcia. (C) Opportunity traverse elevation, extracted from HiRISE DTM. Significant campaigns at Eagle, Endurance, Erebus, Victoria and Santa Maria craters are plotted in color. The plains surrounding Santa Maria crater are approximately 100 m lower in elevation than those surrounding Victoria crater.

2. Geologic setting and methods

Santa Maria is a relatively young impact crater located at 2.172°S, 5.445°W. It is approximately 100 m in diameter and 11–17 m deep (Watters et al., 2011). Topographic measurements made by the Mars Orbiter Laser Altimeter indicate that the plains surrounding Santa Maria crater are approximately 100 m lower in elevation than those surrounding Victoria crater. If bedding is horizontal, as is reconstructed for Victoria crater (see, for example, Hayes et al., 2011), bedrock at Santa Maria crater should represent a substantially lower stratigraphic section than anything examined to date. *Opportunity* explored the crater during sols 2450–2551, and performed an extensive imaging campaign as it drove around the crater from the western rim to the southeastern rim. The stratigraphy exposed in crater walls is not intact and the rover did not drive down into the crater, but *Opportunity* was able to perform detailed analyses of several ejecta blocks.

The *Opportunity* rover's Panoramic Camera (Pancam) and Microscopic Imager (MI) were used to distinguish sedimentary structures and textures. Pancam is a multispectral imaging system mounted on the rover's mast, 1.5 m above the ground. It consists of two cameras, each containing an eight-position filter wheel, allowing multispectral observations in the 400–1100 nm wavelength range (Bell et al., 2003). The MI acts as a "hand lens" camera and is mounted on the rover's "arm", known as the Instrument Deployment Device (IDD). To compensate for the variable topography of rock targets and limited depth-of-field, MI images are usually taken as a stack of images. The IDD moves along a path normal to the surface, and acquires images every few millimeters. MI images have a pixel scale of 30 μm/pixel (Herkenhoff et al., 2003). The Alpha Particle X-ray Spectrometer, also located on the rover's arm, provides bulk elemental characterization (APXS; Gellert et al., 2006).

3. Multispectral observations

Pancam multispectral images obtained during the Santa Maria campaign reveal several Santa Maria ejecta blocks with spectral behavior different from that observed in typical Meridiani outcrop, soils, or ejecta blocks at other craters. Specifically, ejecta blocks named Juan de la Cosa (sol 2451), Sancho Ruiz (sol 2452), Maestre Alonso (sol 2452), Terreros (sol 2479), Ruiz Garcia (sol 2479; Fig. 2), Mabuya (sol 2523), and several other un-named blocks imaged along the rim of Santa Maria exhibit higher reflectivities—from a few percent up to 25%—in the shortest wavelength Pancam filters (432, 482, and 535 nm). In addition, the cleanest (least dusty) parts of these rocks typically exhibit less negative near-IR spectral slopes, and a weaker near-IR "mafic" band (representing the presence of Fe), than either typical Meridiani outcrop (e.g., Farrand et al., 2007) or other spectrally-anomalous "blue" rocks, like those studied along the rim of Victoria crater (e.g., Squyres et al., 2009). Thus, while there are some general color similarities with

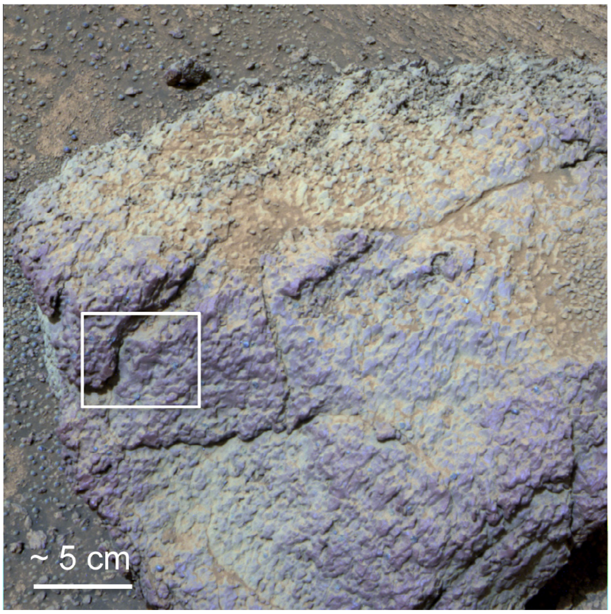

Fig. 2. Target Ruiz Garcia. False color Pancam image using filters L257 (753, 535, 432 nm) acquired on sol 2521. Ruiz Garcia is massive and has a nodular appearance. White box shows approximate location of MI mosaic in Fig. 5. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

rocks near Victoria and other craters, these Santa Maria rocks appear to represent a different Pancam spectral class among Meridiani materials (e.g., Squyres et al., 2006b, 2009; Farrand et al., 2007; Arvidson et al., 2011). Relatively higher reflectivity in the blue as well as relatively weaker near-IR absorption are both consistent with a lower ferric iron content and/or finer grain sizes within these materials (Gaffey et al., 1993; Bell et al., 1993). Following the methods of Rice et al. (2010), none of these surfaces exhibit evidence of hydration based on long-wavelength Pancam data.

4. Textural observations

High-resolution (several mm/pixel) Pancam images of ejecta blocks acquired during the Santa Maria campaign also reveal sandstones with abundant mm-scale, parallel-sided lamination (Fig. 3). These fine laminae, known as pinstripe lamination, may represent wind ripple stratification, or amalgamated grain flows, indicative of eolian deposition (Hunter, 1977; Rubin and Hunter, 1982; Fryberger and Schenk, 1988). Blocks also contain abundant spherules that are similar to those seen elsewhere in Meridiani and interpreted to be diagenetic concretions (e.g., Squyres et al., 2004). In general, rocks near Santa Maria are similar to the strata of the Burns formation studied elsewhere at Meridiani (cf., Grotzinger et al., 2005).

However, the anomalously "blue" ejecta blocks exhibit a very different textural component that consists of massive, fine-grained, mottled, and/or nodular morphologies (Fig. 4). One of the rocks with an unusual texture, named Ruiz Garcia, was selected for a more extensive IDD campaign of MI imaging and APXS characterization. MI images show that this rock appears more well-cemented, and lacks the pore spaces, vugs, and crystal molds that are typical of the Burns formation (cf., McLennan et al., 2005). Ruiz Garcia contains abundant nodules that are well rounded and display morphologies that generally range from ellipsoidal to more irregular shapes that show interlocking geometry (Fig. 5). Note here that the term nodule is used to refer strictly to the morphology, as the precise composition of the nodules themselves cannot be determined. Fig. 5a shows several concretions (gray tone) scattered amongst the more uniform nodular texture (reddish tone). Nodules in the fine-grained facies are typically 3–7 mm as measured along their long axis. Ruiz Garcia is pervasively overprinted by a nodular texture, and the nodules do not appear to have any preferred orientations.

MI images of Ruiz Garcia (Fig. 5) reveal that the rocks have grain sizes smaller than those that can be resolved by the MI. The pixel size of the MI is 30 μm, and several pixels are required to resolve a grain, and so we accept the minimum resolution to be ~100 μm (Herkenhoff et al., 2003). Since, by definition, muds are less than 62.5 μm, including sediments of chemical origin (Blatt et al., 1980) mud sized grains cannot be resolved in MI images. Therefore, we infer that the rock is simply very fine-grained, and could potentially represent something fine enough to be considered a mudstone. These rocks are interpreted as the first sedimentary rocks observed by the rover at Meridiani Planum with grain sizes smaller than that of fine-grained sand. *Opportunity* did not make MI measurements on any other blocks of unusual spectral character, but Pancam images indicate that other anomalously blue Santa Maria ejecta block surfaces are also massive and likely very fine-grained, with rough surface expressions (Fig. 4).

5. Composition

APXS data provides additional insight and can be used to relate the Santa Maria facies to other outcrops at Meridiani Planum. The

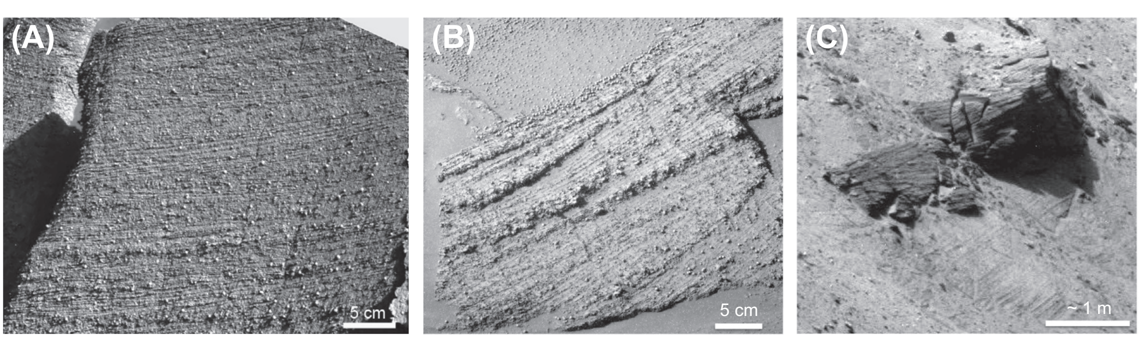

Fig. 3. (A) Typical eolian stratification of the Burns formation, seen here at the Tipuna outcrop, Endurance crater (Grotzinger et al., 2005). This image was acquired using Pancam's 432 nm filter on sol 307. (B) Sandstone ejecta block at Santa Maria crater, with planar to low-angle cross-stratification and pinstripe lamination, indicative of eolian deposition. Note the similarities in scale and style of stratification compared to the Tipuna block in (A). This image also reveals abundant spherules, found within the block and as a lag deposit covering the surrounding loose sediment. This image was obtained using Pancam's 432 nm filter on sol 2539. (C) Pancam image of likely intact stratigraphy within Santa Maria crater. The image reveals multiple sets of cross-beds, consistent with an eolian depositional environment, and similar to rocks of the Burns formation (Grotzinger et al., 2005). The image was obtained using Pancam's 432 nm filter on sol 2544.

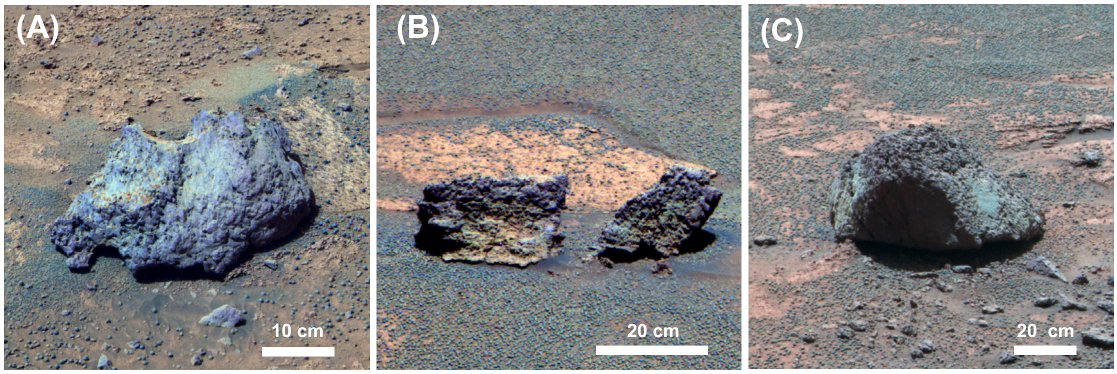

Fig. 4. False color Pancam images of anomalously blue ejecta blocks at Santa Maria crater. (A) Target Terreros, acquired on sol 2479, using filters L257 (753, 535, 432 nm). (B) Target Sancho Ruiz, acquired on sol 2452, using filters L257 (753, 535, 432 nm). (C) Target Maestre Alonso, acquired on sol 2452, using filters L256 (753, 535, 482 nm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

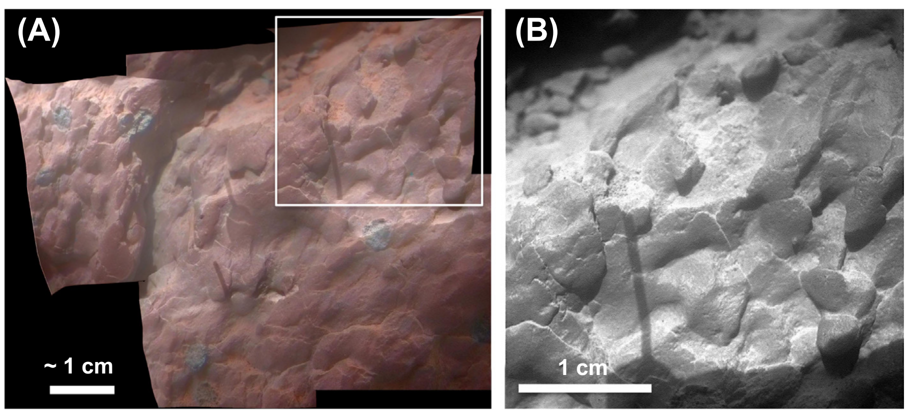

Fig. 5. (A) MI mosaic acquired on sol 2527, colored with Pancam from sol 2521, using filters L277 (753, 432, 432 nm). Individual grains cannot be resolved in MI images. Blue circular areas are hematite concretions, similar to those found elsewhere in Meridiani Planum. White box shows approximate location of MI frame shown in (B). (B) MI best focus frame acquired on sol 2527. Note the nodular texture, very fine grain size, and lack of stratification. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Burns formation is interpreted to represent a two-component mixture of a sulfate- and hematite-rich brine and a siliciclastic component with a composition consistent with acid-leached basalt (McLennan et al., 2005; Squyres et al., 2006b). At Endurance and Victoria craters, these two components have been shown to have a depth dependent relationship, with stratigraphically lower samples enriched in the siliciclastic component, and stratigraphically higher samples enriched in materials precipitated from a sulfate- and hematite-rich brine (Squyres et al., 2006b, 2009). APXS compositional data indicate that the Santa Maria mudstones are sulfate-rich, though relatively enriched in the siliciclastic component (Fig. 6). This is consistent with the low stratigraphic level of Santa Maria crater relative to Victoria and Endurance Craters (Squyres et al., 2009).

Some caution must be applied when relating the composition of the Ruiz Garcia analysis, which was collected on a rock that was not abraded by the Rock Abrasion Tool (RAT), to analyses collected on abraded rocks. Because such "as is" analyses may be variably contaminated with the ubiquitous basaltic soil and dust observed at Meridiani Planum, it is important to evaluate the effect of such contamination on a given APXS analysis. As shown in Fig. 6, for "as-is" analyses there is a clear trend from the mixing array between siliciclastic and chemical components defined by the abraded rock analyses toward basaltic soils. Some basaltic soils are further modified by enrichment in hematite from eroded Burns formation outcrop, as demonstrated by Yen et al. (2005). Based on bulk chemistry alone, Ruiz Garcia compositions appear relatively unaffected by basaltic soil contamination. Interpretation of APXS data (Fig. 6) is consistent with the absence of observed soil or dust components on the outcrop (Fig. 5). Accordingly, we suggest that the Ruiz Garcia analysis faithfully records the composition of the rock, unaffected by soil or dust contamination. This composition indicates that Ruiz Garcia is sulfate-rich (SO_3 = 17.5 wt%, and when paired with MgO, CaO or FeO, the equivalent salt content can represent a significant fraction of the rock). For the major element composition of Ruiz Garcia in relation to other rocks at Meridiani Planum, see Gellert et al. (2006) and Gellert and Rieder (2006).

6. Diagenetic considerations

Despite the relative enrichment of siliciclastic-component in Santa Maria mudstones, the Ruiz Garcia analysis indicates that this lithology is sulfate-rich. This is significant because sulfate sediments are chemically labile, easily recrystallized, and grain sizes are often significantly increased beyond their original primary grain size as a result of diagenesis (McLennan et al., 2005). This increase in grain size is the product of Ostwald ripening of crystals, where recrystallization results in grain-size enlargement to thermodynamically more stable geometries (Lifshitz and Slyozov, 1961). Thus, the grain sizes ($<\sim$100 μm) observed in the unique rock surfaces of Santa Maria ejecta blocks are likely larger than the original, pre-diagenetic grain sizes of their precursor materials. In addition, the complete lack of physical stratification, so

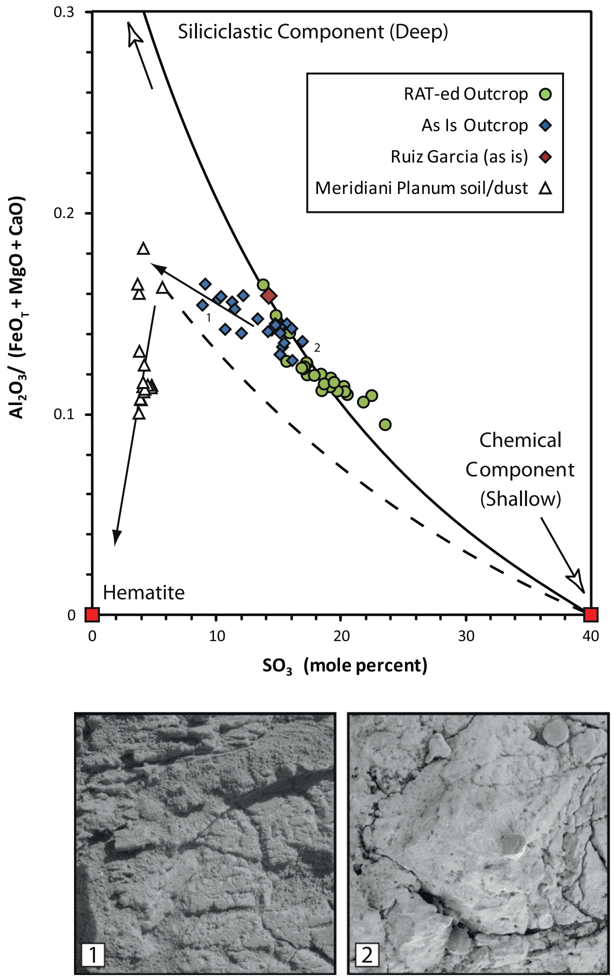

Fig. 6. Molar $Al_2O_3/(FeO_T + MgO + CaO)$ versus SO_3 (mole%) for Burns formation APXS analyses acquired between sol 1 and 700 (Gellert and Rieder, 2006). Green circles are analyses acquired after abrasion of rock surfaces with the RAT, blue diamonds are analyses acquired on "as-is" outcrop (i.e., not abraded or brushed clean with the RAT). The red diamond is the as-is analysis on the target Ruiz Garcia acquired on sol 2521. White triangles are analyses of undisturbed soils and dust at the *Opportunity* landing site collected over sols 1–700. The solid line is a mixing array reproduced from Squyres et al. (2006b) and tracks the varying proportions of siliciclastic and chemical components in abraded Burns formation samples. The dashed line is a mixing array between the chemical component of outcrop (Squyres et al., 2006b) and martian dust, as represented by the analysis Hilltop_Wilson (Yen et al., 2005), collected on sol 123. Lines with small arrowheads track increasing levels of "contamination" of as-is outcrop analyses with basaltic soil, and the enrichment of some of those soils with hematite derived from eroded Burns formation outcrop. The numbers 1 and 2 correspond to the inset MI images of the most SO_3-poor and SO_3-rich as is APXS analyses: "Pohutu" and "Russett", respectively. These images were collected on sol 311 and 381, respectively, and show that the apparent trend away from the mixing array is consistent with variations in soil cover content. Each MI image is 3 cm wide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ubiquitous throughout the rest of the Burns formation and even in other facies at Santa Maria crater, argue that the grain size of these anomalous ejecta block materials is homogeneous and could indeed be significantly finer than ∼100 μm. Sulfate mobility is an issue for all Meridiani rocks, and recrystallization is observed at Endurance, Erebus and Victoria craters (Grotzinger et al., 2005; Metz et al., 2009; Edgar et al., 2012). However, recrystallized rocks at these other locations still preserve primary stratification (Fig. 7), and nodules are not observed. The massive, fine-grained, nodular blocks at Santa Maria crater are exceptional, and another hypothesis is warranted.

We believe that these multiple lines of multispectral and textural evidence support the hypothesis that the unique, massive, fine-grained facies of Santa Maria ejecta blocks could have started out as a mudstone and has since been modified through diagenesis. An important component of this hypothesis is that these sediments could not have started out as the sandstones of the Burns formation, typically with medium to coarse grain sizes (see, for example, Grotzinger et al., 2005, 2006; Edgar et al., 2012); rather, they appear to represent a different initial grain size that was significantly finer.

7. Interpretation of nodular texture

Ruiz Garcia and other fine-grained blocks have a nodular appearance, which we infer to result from differential cementation during diagenesis. Their ellipsoidal to irregular shapes strongly contrast with the concretions that are present in other outcrops of the Burns formation, which generally have strictly spherical shapes (McLennan et al., 2005; Edgar et al., 2012). Ruiz Garcia and other fine-grained rocks lack any visible porosity, in contrast to other Burns facies, and appear very well cemented.

Observations of coarser-grained, well-laminated sandstones in the Santa Maria region suggest that these also underwent differential cementation, as they uncommonly also have a nodular appearance (Fig. 8). However, the coarser-grained facies retain original textures such as lamination, and the nodules in this facies are elongated along bedding planes. Formation of nodules is characteristic of chemical sediments and it is not uncommon to see fine-grained sediments with primary stratification undergo transformation to a more massive but mottled texture due to differential early cementation (Mohamad and Tucker, 1976; Moller and Kvingan, 1988; Lee and Kim, 1992). Ruiz Garcia displays mottled textures that are very similar to nodular mudstones on Earth (Jenkyns, 1974; Kennedy and Garrison, 1975; Moller and Kvingan, 1988). For example, in the Neoproterozoic Buah Formation of Oman one can trace cm-scale stratification laterally and vertically into zones of mottling with massive texture (Fig. 9). The scale and fabric of this terrestrial analog (carbonate) is very similar to the fine-grained martian sediments (likely sulfate).

The formation of nodules can be explained by differential cementation related to early diagenesis. This requires interstitial pore fluids that are oversaturated with respect to the phases that precipitate the interstitial cements that form the nodules. Differential cementation results from heterogeneous nucleation, and differential weathering of the more resistant nodules (better cemented, harder rock) produces the modern surface topography of the rock featuring its characteristic roughness that reflects the presence of the nodules (cf. Noble and Howells, 1974; Kennedy and Garrison, 1975; Moller and Kvingan, 1988).

An alternative interpretation is that the nodular texture represents aggregates of fine particles, similar to peds formed in clay-rich soils. Blocky textures can form in clay-rich soils through wetting and drying or freezing and thawing, with clay films acting as binding agents for larger aggregates (Schaetzl and Anderson, 2005). Peds are often blocky and may be subangular, but do not show the rounded and ellipsoidal shapes observed in Ruiz Garcia. While peds can have elongated shapes, they are elongated in the vertical direction, rather than horizontally along bedding planes, as observed in Fig. 8. It is also difficult to recognize peds in the rock record, due to compaction and alteration (Retallack, 2001). The round and ellipsoidal shapes of the nodules, and their presence in the coarser-grained sandstone facies as well as the fine-grained facies is more consistent with differential cementation related to early diagenesis.

Unfortunately, the stratigraphic context of our hypothesized nodular mudstone facies at Santa Maria is poorly constrained.

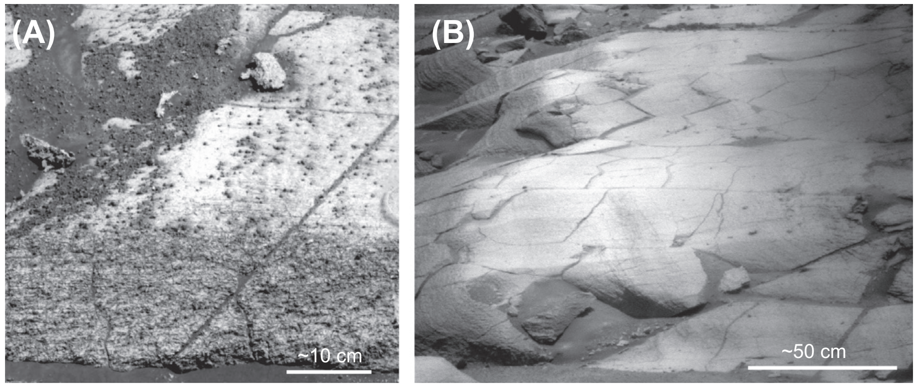

Fig. 7. Recrystallization in the Burns formation seen at Endurance crater and Victoria crater. (A) The Whatanga contact at Endurance crater is interpreted to have formed in the capillary fringe of the water table (Grotzinger et al., 2005). The dark-toned zone is heavily recrystallized, but palimpsest fine lamination is still visible. Image acquired on sol 312, using Pancam's 753 nm filter. (B) The light-toned Smith unit at Victoria crater is heavily recrystallized, but images taken at low solar incidence angles reveal fine lamination (Edgar et al., 2012). Image acquired on sol 1351, using Pancam's 753 nm filter.

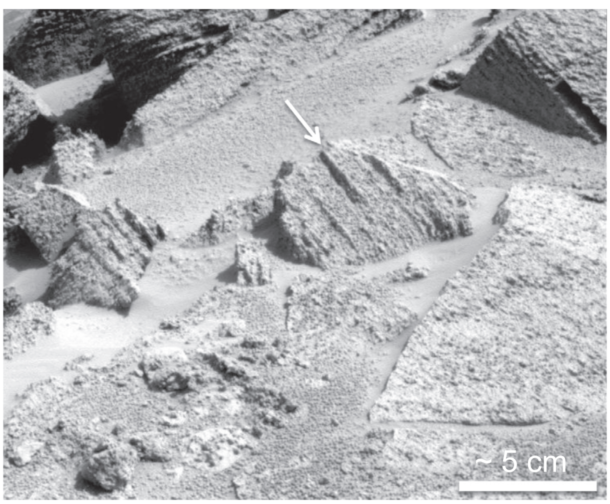

Fig. 8. The coarser-grained, well-laminated sandstone facies also exhibits a nodular appearance (arrow), due to differential cementation. However, the coarser-grained facies retains its original laminated texture. This image was acquired on sol 2456, using Pancam's 753 nm filter.

Pancam images of the crater walls indicate that the nodular, mottled texture is present in only the lower portion of the crater, but impact brecciation inhibits direct inference of stratigraphic position. The proposed mudstones are not observed in stratigraphic context, but we can still infer that they come from a lower stratigraphic level than the sandstones because differential cementation appears to have only affected the lower portion of the observed stratigraphy at Santa Maria crater (Fig. 10).

8. Identifying and interpreting mudstones on Mars

On Earth, fine-grained sedimentary rocks (grain size <62.5 μm) are the most abundant sedimentary rock type (Potter et al., 1980). Mudstones occur in a variety of environments including marine environments, transitional environments such as deltas, rivers and estuaries, and non-marine environments including lakes, floodplains, loess, and other eolian deposits (Potter et al., 1980). Fine-grained extrabasinal sediments – derived far from the site of deposition – are the record of extreme hydraulic segregation resulting from transport in currents of water or air. They accumulate in both local and terminal sediment sinks, and are most abundant at the distal end of sediment transport pathways.

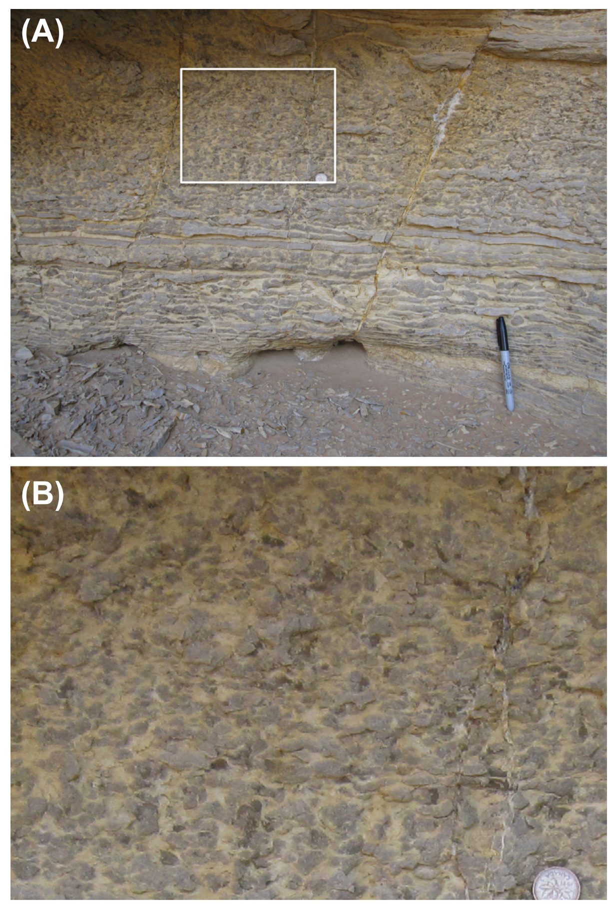

Fig. 9. Diagenetic modification to a massive but mottled texture is common in fine-grained chemical (carbonate) sediments on Earth. This example from the Neoproterozoic Buah Formation of Oman shows a finely laminated texture (base of outcrop in image A) breaking up into nodules (image B). Image B exhibits a massive, fine-grained texture similar to target Ruiz Garcia.

Fine-grained intrabasinal sediment of chemical origin, however, is produced at or near the site of deposition and their grain size reflects nucleation and growth kinetics rather than hydraulic processing (Bathurst, 1975).

Observations of the fine-grained facies at Santa Maria crater are very limited, so it is difficult to determine the environment in which they were deposited. Regional context provided by other

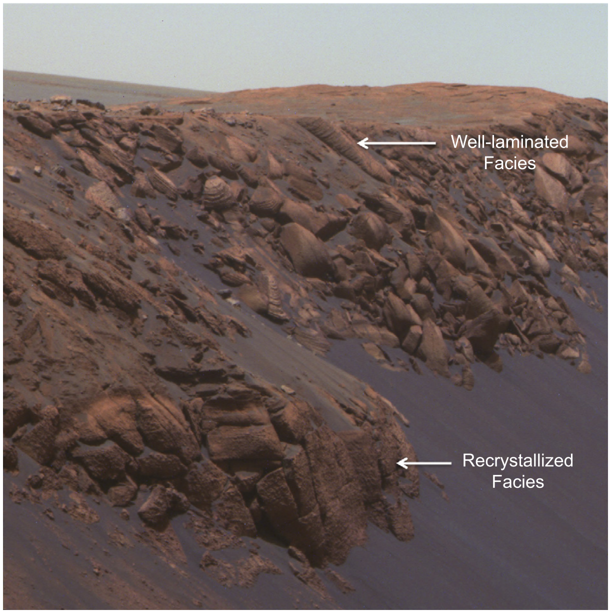

Fig. 10. Stratigraphy exposed in the southern wall of Santa Maria crater. The lower portion of the stratigraphic section appears to be recrystallized, while the upper portion of the stratigraphy is well-laminated. Pancam false color image acquired on sol 2454 using filters L257 (753, 535, 432 nm).

outcrops of the Burns formation suggests it is unlikely that they were deposited in a marine environment. This is due principally to the absence of facies indicative of marine processes and, rather, the preponderance of evidence supportive of eolian processes (see, for example, Grotzinger et al., 2005 for further discussion).

Of the non-marine environments, we see no evidence for larger scale fluvial deposits in the Burns formation, such as channel deposits, coarse lags, or fining-upward sequences, which might support a hypothesis involving settling of fines on flood plains. Volcanic ash is a possible explanation for the fine-grained material, but we see no specific evidence of volcanism in the vicinity of Santa Maria crater besides the ubiquitous basaltic sand that is found across all of Meridiani. Fine-grained material created during impact cratering is also a possible explanation. Fallout of suspended fine sediments from either the atmosphere (which may include pyroclastic or impact-generated fines) or from the water column of a lake may be the two most likely environments that would account for the fine-grained, nodular rocks at Santa Maria crater.

Large accumulations of wind-blown dust and silt – sediments <0.62 μm in grain size – are known as loess, and their cemented rock equivalents loessite (Smalley and Leach, 1978; Johnson, 1989; Chan, 1999; Soreghan et al., 2002). On Earth, loess deposition is most commonly associated with Quaternary glaciation and wind reworking of glacial deposits (Edwards, 1979). Smalley and Krinsley (1979) suggest that there are likely loess deposits on Mars. Loess deposition is proposed as a hypothesis for some of the young, widespread mantling deposits on Mars (Malin and Edgett, 2000), including those within the Medusae Fossae Formation (Greeley and Guest, 1987; Scott and Tanaka, 1986; Head and Kreslavsky, 2004), in Arabia Terra (Fassett and Head, 2007; Mangold et al., 2009; Lewis et al., 2008), Tharsis Montes (Bridges et al., 2010), and within the uppermost strata of the Gale crater mound (Anderson and Bell, 2010; Thomson et al., 2011). Recognition of the importance of these potential loess or dust deposits, which sometimes exhibit evidence for induration and form weakly cemented rock has led to the term "duststones" (Bridges and Muhs, 2012). These duststones likely have global stratigraphic importance and may reflect the long-term decrease of impact-generated fines to be reworked by the wind and transported to sites of regional deposition (e.g., Bridges and Muhs, 2012; Grotzinger and Milliken, 2012). Impacts, explosive volcanism and mechanical breakdown of material through saltation provide alternatives to glaciation as mechanisms to produce abundant fine-grained sediment.

Large dust storms are common phenomena on Mars (Haberle, 1986; Martin and Zurek, 1993; McKim, 1996). We can only estimate their magnitude in the geologic past, and the potential for rare, large storms to carry large volumes of sediment. It is possible that fine-grained facies at Santa Maria crater were formed during the fallout following dust storms that occurred at the time the Burns formation was being deposited. Although *Opportunity* did not observe what lies stratigraphically beneath the fine-grained rocks at Santa Maria crater, we can infer that it was likely eolian sandstone, because we see outcrops of eolian sandstones on the plains between Santa Maria crater and Endeavour crater at successively lower elevations. Fines deposited during global dust storms would have draped and mantled pre-existing topography. When wind velocities later increased (the coarser cross-bedded deposits of the Burns formation suggest persistent high wind velocities), much of the dust would have been removed, but perhaps some fraction remained in place to create the observed deposit. This potential "duststone" deposit would have mostly been preserved in an interdune depression as a lens of massive fine-grained material interfingered with eolian sandstones.

It is important to note that the APXS composition data for Ruiz Garcia are not consistent with the composition of modern martian dust (based on the analysis of Hilltop_Wilson (Yen et al., 2005), collected on sol 123). While it is possible that the composition of ancient martian dust was different, resulting in a composition that falls on the siliciclastic to chemical mixing array rather than the mixing array between dust and the chemical component (Fig. 6), the inconsistent composition between Ruiz Garcia and modern martian dust leads to another hypothesis.

Alternatively, we consider a possible lacustrine origin for the fine-grained material. Lakes are sinks for both water and sediment (Leeder, 2011). They form when runoff or river flow is interrupted, usually in a depression, or when groundwater emerges within interdune depressions or other playa lake settings. Lakes lack high current velocities, which provides a simple hydraulic setting in which fines can settle from suspension, making this an attractive interpretation for the Santa Maria fines. Previous work shows that interdune depressions would have been common on the ancient Meridiani plains (Grotzinger et al., 2005; Edgar et al., 2012). There are many types of lakes, ranging from large, deep, permanent freshwater lakes, to shallow, ephemeral, saline lakes, and they can be distinguished on the basis of facies associations and suites of sedimentary structures. We see no evidence in Meridiani for large, deep, permanent lake facies such as turbidites and varves, or associated adjacent fluvial facies that would have supplied a lacustrine setting with sediment, such as channels, alluvial fans, or deltas. Given the eolian environment that characterizes the Burns formation, this type of lake would have been unlikely. However, mudstones are found in terrestrial eolian environments in ephemeral saline lakes (Hanley and Steidtmann, 1973; Mountney and Thompson, 2002). Ephemeral saline lakes leave deposits of interstratified evaporites and extrabasinal clastic sediments, produced by cycles of storm runoff followed by evaporite precipitation (Leeder, 2011). Chemically purer, more massive mudstones form when groundwater emerges, evaporates, and leaves its salts as mud-sized sediment particles. Lacustrine mudstones in eolian environments may additionally contain structures such as desiccation cracks, or coarser evaporite crystal growth structures. Whereas possible desiccation cracks were observed in sandstones at Erebus crater (Grotzinger et al., 2006; Metz et al., 2009), we do not see these features in the proposed mudstones at Santa Maria crater. Instead, the fine-grained facies appears homogenous, with very low porosity, consistent with a pervasively cemented interdune chemical sediment, produced by in situ evaporation of emergent groundwater.

A key attribute of the Ruiz Garcia fine-grained facies is its nodular texture, and absence of visible pores, vugs, or crystal molds. On Earth, such a texture can indicate significant early diagenesis involving heterogenous lithification as discussed above. In addition to early lithification, the development of nodular texture may also be enhanced by differential compaction of less-well cemented components of the rock around the nodules during shallow burial (Wolf and Chilingarian, 1976; Potter et al., 1980). In the case of evaporites, nodules may reflect diagenetic phase changes from primary to secondary mineral assemblages, such as during the conversion of gypsum to anhydrite (Murray, 1964). Either scenario could have occurred during diagenesis of lacustrine sediments. However, the absence of vugs, larger evaporite crystals, or crystal pseudomorphs suggests the sediment was precipitated as fine mud and experienced only enough diagenesis and recrystallization to form nodules, similar to the example of nodular carbonate mudstones (Fig. 9). This would suggest precipitation from the water column, very rapidly and with many nucleation points to form abundant small crystals. The absence of bottom growth crystals, with an upward growth direction, would rule out persistence of the water body for a period of time long enough to form these crystals. In summary, we believe that the evidence from observations of the anomalous ejecta blocks at Santa Maria crater fits a simple model for a transient evaporitic lake (Fig. 11) that precipitated fine-grained sediments that were shallowly buried and recrystallized to form nodular mudstones. Compared to Eagle and Endurance craters, this implies a body of standing water, as opposed to just flowing water; however, it need not have been long lived.

9. Significance of duststones and mudstones on Mars

Although we are unable to distinguish potential duststones from lacustrine mudstones at Santa Maria crater due to limited data, the occurrence of this fine-grained facies still has important implications. Regardless of their origin, this is a new occurrence of such fine material at Meridiani Planum. It has been proposed that dust may comprise a much greater portion of the global stratigraphic record on Mars compared to Earth (Bridges and Muhs, 2012; Grotzinger and Milliken, 2012). Thus, if their origin is dust-related, the fine-grained material at Santa Maria crater may shed light on preservation mechanisms and how dust is incorporated in the stratigraphic record, and would provide another expression of persistently dry conditions that may have existed for much of the geologic history of Meridiani Planum.

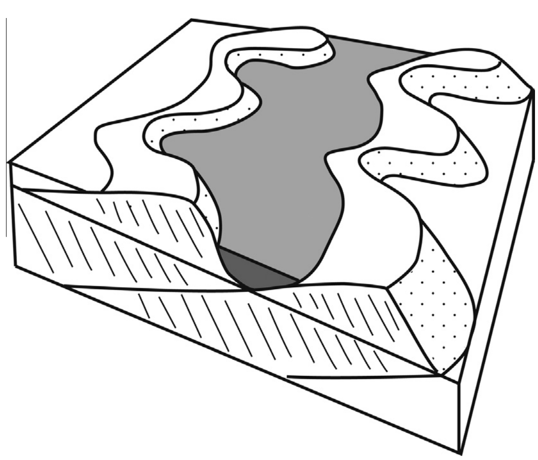

Fig. 11. Schematic model of an interdune lake. Shaded zone represents a flooded an interdune area, where emergent ground water filled the topographic low. The Santa Maria mudstones could have formed in a transient evaporitic lake like this, surrounded by eolian deposits.

Alternatively, if the fine-grained rocks represent lacustrine mudstones, this would support the inference that the Burns formation may record intermittently wet conditions (Squyres et al., 2004), possibly involving interdune lacustrine environments (Grotzinger et al., 2005). This is especially important because it strengthens the conceptual model that invokes sulfate-rich, but "dirty" (i.e. silicate containing) playa lakes as a potential source of the Burns formation eolian sulfate sandstones. The sulfate-rich eolian sandstones that overlie the fine-grained sediments would signal a return to dry conditions at ancient Meridiani. Diagenetic alteration during shallow burial of the fine-grained sediments created the nodular textures, and all sulfate sediments experienced the chemical interactions that resulted in ubiquitous precipitation of hematite concretions that overprint both nodular fine-grained sediments as well as coarser sandstones.

Finally, it is worth noting the special significance of the lacustrine hypothesis. Given that lakes of any type have high potential to preserve organic compounds, the Ruiz Garcia fine-grained sediments could represent not only a former potentially habitable environment, but one that also could have trapped organic matter if it had been present (cf. Farmer and Des Marais, 1999; Summons et al., 2011). Yet it is important to note that most organics are unstable in the presence of Fe(III) which is abundant in Meridiani Planum (Sumner, 2004). While the Santa Maria mudstones represent a potentially habitable environment, evidence for interactions with water in the presence of Fe(III) minerals makes preservation of organic compounds in these rocks unlikely. Recognition of diverse facies or diagenetic textures does not in its own right guarantee success in exploring for organics (assuming organic compounds were present), but rather defines a basis by which exploration can proceed systematically, with emphasis on those rocks which may have undergone early lithification before organic compounds could have been degraded. This exploration approach is already being put into practice by the Mars Science Laboratory rover *Curiosity*, which has recently confirmed the first clay-rich mudstones in Gale crater (Grotzinger et al., 2014). Ongoing and future missions will continue to refine our understanding of potentially habitable environments.

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