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Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars

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Abstract

The MER rover Opportunity has carried out the first outcrop-scale investigation of ancient sedimentary rocks on Mars. The rocks, exposed in craters and along fissures in Meridiani Planum, are sandstones formed via the erosion and re-deposition of fine grained siliciclastics and evaporites derived from the chemical weathering of olivine basalts by acidic waters. A stratigraphic section more than seven meters thick measured in Endurance crater is dominated by eolian dune and sand sheet facies; the uppermost half meter, however, exhibits festoon cross lamination at a length scale that indicates subaqueous deposition, likely in a playa-like interdune setting. Silicates and sulfate minerals dominate outcrop geochemistry, but hematite and Fe3D3 (another ferric iron phase) make up as much as 11% of the rocks by weight. Jarosite in the outcrop matrix indicates precipitation at low pH. Cements, hematitic concretions, and crystal molds attest to a complex history of early diagenesis, mediated by ambient ground waters. The depositional and early diagenetic paleoenvironment at Meridiani was arid, acidic, and oxidizing, a characterization that places strong constraints on astrobiologial inference.

Keywords: Mars; Meridiani; sedimentology; astrobiology

1. Introduction

The scientific objectives of the Mars Exploration Rover (MER) mission are to explore two sites on the martian surface and to determine whether environmental conditions there ever were suitable for life. The rovers Spirit and Opportunity have spent more than a year and a half on the surface of Mars, exploring their landing sites at Gusev crater and Meridiani Planum, respectively. One of the principal discoveries of the MER mission is ancient sedimentary rocks, exposed in craters and along fissures in the Meridiani plain. These beds have provided the first opportunity to investigate the sedimentology, stratigraphy, and geochemistry of sedimentary rocks at the outcrop scale on another planet. In this paper and others in this issue, we describe and interpret the sedimentary rocks discovered by Opportunity, expanding on initial results presented earlier [1,2]. Our central finding is that the beds exposed at Meridiani preserve a rich record of past aqueous processes on Mars, including both subsurface and surface water. Conditions there may have been suitable for some forms of life, at least transiently, although the Meridiani environment also would have presented some substantial challenges to biology.

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The MER rovers are solar-powered, six-wheeled robotic vehicles capable of executing long traverses across the martian surface. Each rover carries a copy of the Athena science payload [3]. The key elements of the payload are:

- ***Pancam*** (Panoramic camera), a high-resolution, multispectral, stereo imaging system [4].
- ***Mini-TES***(Miniature Thermal Emission Spectrometer), an infrared spectrometer that performs remote sensing over a wavelength range from 5–29 μm [5].
- ***Microscopic Imager***, a camera that provides close-up imaging of an area 3×3 cm in size with a resolution of 30 μm/pixel [6].
- ***APXS*** (Alpha Particle X-Ray Spectrometer), an in situ instrument that determines the abundances of major and some minor elements [7].
- ***Mössbauer Spectrometer***, an in situ instrument that identifies and determines the relative abundances of Fe-bearing phases [8].
- ***RAT*** (Rock Abrasion Tool), a tool that can brush or abrade a rock surface, exposing subsurface materials for the other instruments to investigate [9].

Opportunity landed on January 24, 2004, coming to a stop in a small impact feature, about 20 m in diameter, that we named Eagle crater [1]. This landing location was fortuitous, as the walls of the crater exposed outcrops of layered rock, tens of cm thick, that were readily accessible to the rover (Fig. 1). Opportunity spent the first 57 martian days, or "sols," of its mission exploring within Eagle crater, focusing primarily on the outcrop. Many of the fundamental discoveries from which our interpretation of Meridiani sedimentary rocks has emerged were made within this crater.

After exiting Eagle crater, Opportunity drove approximately 800 m eastward across flat, nearly featureless plains to another much larger crater that we named Endurance (Fig. 2). Endurance crater is about 150 m in diameter and 20 m deep, and its walls expose a substantially greater thickness of layered rock than Eagle crater does. We used the rover initially to survey Endurance crater from points along its rim, obtaining Pancam images and Mini-TES spectra of the interior from several locations. At the same time, MER project engineers conducted extensive tests to determine whether Opportunity could safely descend and ascend the steep walls within the crater. After determining that the rover could operate on rocky slopes as steep as ~30°, we made the decision to send Opportunity into Endurance crater.

Opportunity entered Endurance on Sol 134 of its mission. Over a period of several months, we drove the rover down a steep slope at a location on the crater wall dubbed "Karatepe West," grinding with the RAT to expose layered sedimentary rock at eleven locations. The result was the first stratigraphic section ever measured on another planet.

After reaching the base of the accessible section at Karatepe West, we explored near the bottom of the crater for a time, and then began a long and arduous ascent to a feature high on the southern wall of the

Fig. 1. Composite Pancam image of sedimentary rocks exposed in blocks along the wall of Eagle crater, Meridiani Planum, Mars. Note bedding, small scale festoon cross lamination, and the hematititc concretions dubbed "blueberries." About 35 cm of section is visible in this image.

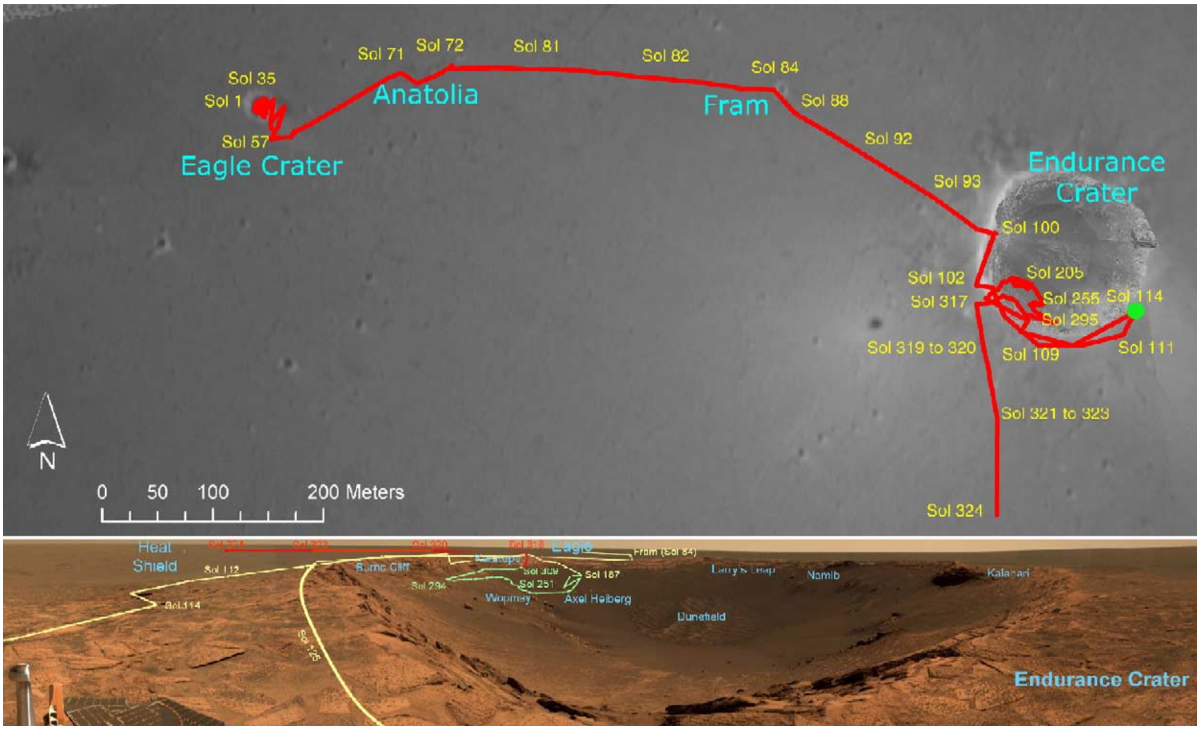

Fig. 2. The traverse of the Opportunity rover, from landing through Sol 324. The upper panel shows the traverse in map view, on a base image obtained using the spacecraft's Descent Image Motion Estimation System (DIMES) camera during the descent to the martian surface. Landmarks indicated include Eagle and Endurance craters, Fram crater, and the Anatolia fracture system [1]. The dark spot just above the letter "S" in "Sol 319 to 320" is the shadow of the vehicle's parachute. The lower panel shows the traverse in oblique view, on a base image obtained by the Pancam camera from a point (indicated with a green dot in the upper panel) on the southeast rim of Endurance crater. Major landmarks in and around Endurance crater are indicated. Rover localization and map generation by R. Li, Ohio State University.

crater that we named "Burns Cliff," after the late Roger Burns of MIT, who predicted some of the key geochemical and mineralogical features discovered by Opportunity. Opportunity reached the base of Burns Cliff on Sol 276 and, while perched at an angle that eventually reached 32°, began to conduct remote and in situ sensing of cliff materials. The investigations within Endurance crater, particularly at Karatepe West and Burns Cliff, provided rich additional details regarding past environmental conditions at Meridiani Planum. Opportunity exited Endurance crater on Sol 315 and proceeded southward in search of additional outcrops. The rover's traverse, from landing to the egress from Endurance crater, is shown in Fig. 2.

In the sections below, we provide an overview of Opportunity's key results at Meridiani, including the depositional origin of the rocks there, their subsequent diagenesis, and the implications for paleoenvironmental conditions, astrobiology, and future exploration. Other papers in this volume develop these themes at length, providing details of observation and interpretation, as well as discussions of relevant physical and chemical analogs on Earth.

2. Origin

2.1. Sedimentology and stratigraphy

Early observations by Opportunity at Eagle crater enabled some noteworthy sedimentological findings [2], but the observations were frustratingly difficult to put into context because of the small amount of stratigraphic section exposed. This paucity of section motivated the traverse to Endurance crater, which was amply rewarded with the observations made at Karatepe West. In this issue, Grotzinger et al. [10] discuss sedimentological and stratigraphic observations at both locations in detail, and infer from them a succession of changing environmental conditions in this part of Meridiani Planum.

Grotzinger et al. [10] divide the Burns formation into distinct lower, middle, and upper units. The total thickness of the three units exposed at Endurance crater is at least 7 m. All three units are observed or inferred to be sandstones, formed from sand grains that are rich in a variety of sulfate salts (see below).

The lower unit of the Burns formation was not sampled directly at Karatepe West, but was observed by Pancam and Mini-TES at the eastern end of Burns Cliff. There it forms a spectacular cross bed set, more than 1.5 m thick, that is truncated and disconformably overlain by the middle unit. Low-angle truncations are abundant within the lower unit. Based on these observations, Grotzinger et al. [10] conclude that the lower unit was formed by migrating sand dunes. The unit could not be observed with the Microscopic Imager because of concerns about rover safety on the steep slopes encountered; therefore, grain sizes remain unknown for this bed.

The contact between the lower and middle units, which is well exposed at the eastern end of Burns Cliff, is interpreted as an eolian deflation surface. Above this contact, the middle unit consists of sandstones that exhibit distinctive fine planar lamination in some locations and low-angle cross-lamination in others. (As noted below, however, lower portions of the middle unit have been so severely recrystallized that lamination is commonly obscured.) Grain sizes typically range from 0.3–0.8 mm within the middle unit; many laminations are only a single grain thick and are composed of grains that are well sorted within laminae. Based on these characteristics, the middle unit is interpreted to be a sand sheet deposit that accumulated as eolian impact ripples migrated across a nearly flat-lying sand surface.

The contact between the middle and upper units is diagenetic rather than depositional in origin. Substantial recrystallization and enhanced secondary porosity are evident in Microscopic Imager images immediately below the contact [10,11], while much less recrystallization is seen above it. There are also distinct transitions in elemental chemistry (and inferred transitions in mineralogy) that are consistent with enhanced diagenetic modification below the contact [12].

Like the middle unit, the lower reaches of the upper unit are also dominated by fine-scale planar laminations and low-angle cross-lamination indicative of origin as a sand sheet. In the upper portion of the upper unit, however, there is a distinct change in sedimentological character. The sandstones here are distinguished by wavy bedding and, most notably, by small-scale festoon cross lamination. This cross-lamination, first described at Eagle crater [2] and subsequently also observed in what we believe to be correlative beds at Karatepe West [10], is interpreted at both locations to result from ripple migration induced by surface flow of liquid water over sand.

Taken together, these observations point to an origin of the explored portion of the Burns formation as a “wetting upward” succession from dry eolian dunes to wet interdune deposits. The lower unit represents the dunes themselves, and the upper portion of the upper unit represents sediments transported in water that pooled on the surface, perhaps between dunes. The sand sheet of the middle unit and the lower portion of the upper unit is transitional, perhaps representing the margin between dry dune and wet interdune deposits. As discussed below, the sulfate-rich sands that comprise all three units owe their origin to aqueous processes.

2.2. Geochemistry and mineralogy

As discussed by Clark et al. [12] in this issue, Mössbauer, APXS, Mini-TES and Pancam spectra collectively indicate that the outcrop matrix throughout all explored portions of the Burns formation contains three main components — silicate minerals, sulfate salts, and oxidized iron-bearing phases, especially hematite. Cation abundances show that outcrop chemistry derives from olivine basalt [11], but electrochemical balance with constituent anions requires that a high proportion of these cations now resides in sulfate (and perhaps minor chloride) minerals. Consistent with this observation, Mössbauer spectra of outcrop surfaces brushed and abraded by the RAT show no evidence of either olivine or magnetite, although these and other Fe-bearing basaltic minerals show up clearly in the unconsolidated sands that are ubiquitous on the Meridiani plain [13]. (Mini-TES does detect olivine in some observations targeted on outcrop material, but this signature is attributed to the basaltic sand that is commonly strewn on outcrop surfaces at scales smaller than Mini-TES’ spatial resolution [14]). Al and Si co-vary across the 19 RATted outcrop samples analyzed to date (including eleven in the stratigraphic section at Karatepe West), with Si in excess of Al, suggesting that both aluminosilicate minerals (phyllosilicates?) and a non-aluminous silicate, possibly free silica, occur as fine-grained components of the outcrop matrix [12].

One sulfate mineral group unambiguously identified by Opportunity’s instruments is jarosite [13]. Jarosite is environmentally informative, because it precipitates only from acidic solutions. Thus, as hypothesized years ago (e.g., [15,16]), sulfuric acid must have exerted a strong influence on basalt weathering and sediment deposition at Meridiani Planum. That jarosite still persists in outcrop indicates that these rocks have not seen water with pH above 4–5 for extended intervals of time since their formation [17–19].

Consistent with Mini-TES observations of the outcrop that reveal evidence for Mg-and Ca-sulfates [14], cation abundances measured by APXS require that Mg-sulfates dominate the sulfate component, with subordinate amounts of Ca-sulfate minerals and jarosite [12]. Additional sulfate minerals may be present in the ferric component identified in Mössbauer data only as Fe3D3 (see below). Insofar as many of the identified or inferred sulfate minerals are hydrated, water of hydration in outcrop rocks likely runs between 1% and 4% by weight [12]. Cl and Br abundances are low, but highly variable among samples, with Cl peaking in stratigraphically lower horizons at Karatepe West, while Br shows a statistically complementary distribution [12]. The large variations in Cl/Br ratio within the outcrop at both Eagle and Endurance may indicate fractionation of chloride and bromide salts via evaporative processes [2,20] or differential mobility facilitated by freezing-point depression of ice [12]. Hematite makes up about 7% of the rock [13]. (A portion of the hematite in outcrops occurs in spherulitic concretions, discussed below, but by weight, a significant fraction must reside in the sand grains and fine grained cements.) A second ferric component present as ~4% by weight is the one identified in Mössbauer spectra as Fe3D3, a designation that refers to a suite of octahedrally coordinated Fe^{3+}-bearing phases that have a mineralogically undiagnostic Mössbauer signature [13]. As illustrated in this issue by the comparative study of Fernandez-Remolar et al. [19] on deposits from Rio Tinto, Spain, modern environments where jarosite and iron oxides precipitate from acidic waters commonly include the ferric iron sulfate mineral schwertmannite as an Fe3D3 mineral. Overwhelmingly, the iron present in outcrop minerals is ferric, indicating oxidizing conditions during deposition and diagenesis.

Overall, geochemical data indicate that the sandstone is what has been called a “dirty evaporite” [2], with silicate minerals derived by aqueous alteration of olivine basalt mixed with sulfate minerals formed by the evaporation of ion-charged waters under acidic, oxidizing, and arid conditions [2,21] and hematite precipitated by early diagenetic ground waters in contact with primary depositional minerals [11,12]. Geochemical models presented in this issue by Tosca et al. [18] indicate that the mineralogy observed or inferred for Meridiani outcrop rocks compares closely with that expected during the evaporative evolution of waters formed during sulfuric acid weathering of olivine basalt.

3. Diagenesis

As detailed by McLennan et al. in this issue [11] the rocks at Meridiani underwent variable and in some cases substantial diagenetic modification after their initial deposition. Most conspicuous among diagenetic phases are the small concretions [2], informally referred to as “blueberries,” that are found in all outcrops observed at Meridiani to date. Blueberries play a major role in the development of an integrated understanding of Meridiani geology, not least because a surface veneer of these spherules, eroded from outcrop rocks, carries the remotely sensed spectral signature of hematite that motivated landing on the Meridiani plain [1,22,23]. The spatial distribution of blueberries in outcrop rocks is overdispersed (*i.e.*, more uniform than random) and their shapes are almost perfectly spherical. These observations suggest that the concretions formed diagenetically in stagnant or very slowly migrating (relative to rates of spherule growth) ground waters that saturated Meridiani sands. Spherules are found abundantly in the eolian sandstones that dominate the lower and middle units of the Burns formation, and also in the water-lain sediments in the upper unit, indicating that ground water percolated through all beds examined to date. The concretions developed in sandy sediments, but no granular texture is visible in their interiors at the resolution of the Microscopic Imager [24]. This observation suggests both that solution was involved in their formation and that the insoluble siliciclastic fraction of outcrop rock is very fine-grained [2].

Mössbauer, APXS, Mini-TES and Pancam data all indicate that spherules consist primarily of hematite [13,14,20,25]. The high concentration of hematite in soils dominated by fractured spherules [13] and Pancam observations of spherules sectioned by the RAT [2] show that hematite concentration is high throughout the spherules, not just as a surface coating. These observations are also consistent with the view that the concretions incorporated the fine-grained siliciclastic component of the outcrop matrix and dissolved more soluble sulfates as they grew [11]. Ground water dissolution of jarosite may have provided the iron for hematite precipitation, but the fact that substantial amounts of jarosite remain in the rocks requires that water-mediated diagenesis did not proceed long enough to convert all the iron in this mineral to oxide (if that was the mechanism), implying that the reaction was shut off either by the attainment of equilibrium or by water removal (i.e., by further evaporation or freezing) from the sediments before equilibrium was reached [11,17–19].

We do not know whether the hematite replaced a precursor goethite phase, but it is not necessary to postulate this, as Fe^{3+}can be transported by and hematite can precipitate directly from acidic water.

Chan et al. [26] proposed goethite-cemented concretions in quartzose sandstones of the Jurassic Navajo Formation, Utah, as terrestrial analogs to Meridiani concretions. In this volume, Morris et al. [27] introduce a different analog, tiny hematitic spherules formed diagenetically as acidic hydrothermal ground waters percolate through basalts in Hawaii. This latter analog has the distinct advantage of containing grey hematite, as inferred for Meridiani hematites by remote sensing from orbit [22,23]. The Hawaiian examples also steer closer to Meridiani paleoenvironments in their association with acidic ground waters and substrates with basaltic ion abundances [27].

A second important class of diagenetic features found within outcrop rock consists of small elongate voids [24] that are distributed abundantly but heterogeneously at both Eagle and Endurance craters. These features, up to ~1 cm long and 1–2 mm wide where they intersect the rock surface, exhibit distinctive lozenge or tabular shapes and are dispersed through the rock at random orientations. The voids have been interpreted as crystal molds formed by the dissolution of soluble minerals [2,24], probably of monoclinic habit. McLennan et al. [11] describe the molds in detail and suggest on the basis of petrographic observations of outcrop paragenesis that they resulted from dissolution of some late-forming evaporitic mineral, perhaps melanterite (a hydrated ferrous sulfate) or Mg-, Fe-, or Ca-chlorides.

Unlike the ubiquitous concretions, crystal molds and other secondary porosity in the rocks are not distributed evenly through the section. They are found in abundance in beds exposed at Eagle crater and in the apparently correlative upper portions of the section at Endurance crater. They are less prevalent, however, in deeper portions of the section where recrystallization has been most pronounced.

Outcrop rocks also include two or more generations of cement [11]. These include both early pore-filling cements that are related to the original lithification of the sediments, and later cements formed by recrystallization. The latter are best developed around spherules, where they cement evaporitic sand grains together to form distinctive spherule overgrowths. When subjected to erosion, the tightly cemented and resistant materials around spherules can form small pedestals or sockets [24]. Cement mineralogy is not well constrained in either instance, but likely candidates include Mg-, Ca-, and Fe-sulfates (including jarosite), chlorides, hematite, and amorphous silica [11].

The distribution of cements is also discontinuous throughout the section. As noted above, secondary cementation/recrystallization is pervasive in the lower portion of the section, in some strata to the point that the primary stratification is no longer evident. While some cements in the lower portion of the section clearly began as overgrowths around spherules, others form spherule-free nodules that apparently developed around other nucleation sites.

The precipitation and recrystallization of cements, the formation and subsequent dissolution of the apparent monoclinic crystals now recorded as molds, the formation of the hematitic concretions, and the precipitation of second-generation cements around spherule surfaces all speak to a complex history of early diagenesis mediated by ground water flow [11]. In contrast, diagenesis postdating the Endurance crater impact appears to have been limited.

4. Ancient environmental conditions at Meridiani Planum

All of the outcrop rocks examined to date at Meridiani Planum are sandstones. The sand grains that form them are dominated by a mixture of fine-grained altered siliciclastic phases and sulfate salts. This is true even for the lower unit of the Burns formation, which was not studied in situ but which has the same sulfate-rich Mini-TES spectral properties as the rest of the sequence. So we interpret the entire Burns formation as owing its origin to the reworking of mixed sulfate-silicate sediments. The initial deposits formed by chemical weathering of olivine basalt in aqueous solutions of sulfuric acid, followed by evaporation to produce sulfate (and perhaps minor other) salts that accumulated with fine grained silicates. Subsequent erosion and redeposition of these materials as sand grains formed the beds observed in outcrop [2]. Thus, even for the portions of the unit deposited by wind, constituent grains trace back to aqueous processes. Because these grains are made of evaporitic material, we infer that an evaporitic source region such as a wet interdune depression or a playa lake was present nearby around the time of their deposition. In a terrestrial example cited by Grotzinger et al. [10], playas at White Sands, New Mexico, supply enough sulfate-rich sand to cover an area of ~450 km^2 with dunes.

The style of reworking of the sand grains in the Burns formation varies within the sequence in a way that suggests the influence of a fluctuating water table

[10]. The lower unit represents an eolian dune environment, overlain by sand sheet deposits that may have formed along dune margins and have been transitional to the water-lain deposits in the upper part of the upper unit. Clearly the lower unit was deposited under arid conditions. However, the irregular, scoured nature of the contact between the lower and middle units led Grotzinger et al. [10] to propose that the lower unit may have been moist or already lightly cemented by the time of the scouring, providing evidence for a rise in the water table after dune formation. The presence of sand sheet deposits above this contact suggests that while the surface may have become damp, it was not yet flooded. However, by the time the water-lain upper part of the upper unit had formed, the water table had risen to and intersected the surface.

The diagenetic history of the rocks at Meridiani also provides evidence for water table fluctuations. As already noted, the contact between the middle and upper units is diagenetic in nature, indicating that ground water stabilized that level for some time. In fact, McLennan et al. [11] cite evidence for as many as four episodes of ground water influx. The first, of course, involves the water that produced the grains that comprise the sands. A second episode may have wetted and lightly cemented the lower unit prior to formation of the scoured contact between the lower and middle units. The third influx culminated in the rise of water to the surface and the development of the subaqueous current ripples in the upper part of the upper unit. This same episode may have led to much of the observed cementation throughout the sequence. A fourth influx resulted in precipitation of the hematite-rich concretions found throughout the Burns formation.

In summary, we interpret the Burns formation to be sedimentary rocks formed in a wind-swept, arid surface environment with a fluctuating water table. Water rose occasionally to the surface, forming pools in which evaporation led to production of sulfate-rich sand grains that were reworked by the wind to form dunes and sand sheets. The rocks observed by Opportunity to date record a transition from dunes to dune-marginal sand sheets to transient pools of surface water. Multiple introductions of ground water governed diagenesis, including the formation of the ubiquitous hematite-rich “blueberries.”

Key characteristics of the Burns formation constrain interpretations of the environmental conditions under which it formed. The unit is dominated by eolian sands, indicating that surface conditions were generally arid. The mineralogy, particularly the presence of jarosite, indicates that ambient waters were acidic. And the oxidation state of iron, with most present as Fe^{3+}even though the unweathered source material was Fe^{2+}in basalt, indicates that conditions were oxidizing. So despite the abundance of water when the rocks at Meridiani formed, arid, acidic and oxidizing conditions prevailed and would have posed multiple challenges for life [21].

The age of the rocks at Meridiani is difficult to determine. An upper bound can be derived from orbital images that show that the Meridiani plains materials disconformably overlie dissected Middle to Late Noachian cratered terrains [28]. The rocks observed by Opportunity therefore could be as old as three to four billion years. In very broad terms, then, the Meridiani beds may be of the same age as sedimentary rocks that record the early evolution of life on Earth.

5. Astrobiological implications

The Athena science payload carried by Opportunity was designed to search for geologic evidence of paleoenvironments that might have permitted life [3], not to search for evidence of life itself. Of the several physical and chemical biosignatures found in ancient terrestrial rocks, only macroscopic bedding features formed by the interaction of microbial communities with physical sedimentary processes might have been detected in Pancam images. They have not been observed. Nonetheless, as explored in this issue by Knoll et al. [19], the characterization of Meridiani paleoenvironments as arid, acidic and oxidizing places important constraints on astrobiological inference.

Obviously, many terrestrial organisms thrive under oxidizing conditions, and some microorganisms also live in strong acids or at low water activity. So, strictly speaking, the ancient Meridiani environment was likely habitable, at least transiently when relatively dilute ground waters saturated accumulating evaporitic sands, at times also pooling on the surface. Of course, geochemical evidence also suggests evaporation to dryness, perhaps several times, and the duration of habitable conditions and the length of time between habitable intervals is unknown.

Even if water was present at Meridiani for a substantial period of time, there are significant complicating factors regarding the suitability for life of the environment recorded there [19]. One key issue concerns phylogeny — the evolutionary relationships of terrestrial extremophiles to the great majority of organisms that live under less extreme conditions. With few exceptions, terrestrial organisms that live in arid, acidic, or oxidizing habitats are derived from ancestors that could not tolerate such environments. Thus, consideration of Meridiani requires that we not only ask whether members of a more broadly distributed biota could adapt to the Meridiani paleoenvironment, but also whether life could originate or gain an early foothold in such a place. Acidic and oxidizing environments present a severe challenge to the type of prebiotic chemical reactions generally thought to have played a role in the origin of life on Earth [19].

Meridiani geology does not tell us whether life could have originated earlier in martian history under different environmental conditions, but any early biota would have been subject to impact frustration during late heavy bombardment. On Earth, deep sea hydrothermal habitats might have provided refuge against large impacts [29], but there is no evidence that the martian surface provided comparable safe houses. Therefore, if Meridiani is representative of the most favorable surface environments that Mars possessed after late heavy bombardment, acidity, oxidation, and increasingly severe cold [30] and aridity [31] would have presented significant challenges to surface biology. We do not know to what extent Meridiani environments were representative of the planet's surface as a whole when the outcrop rocks formed, but the only other martian location explored in similar detail, Gusev Crater, shows evidence for conditions significantly less favorable than those at Meridiani.

6. Implications for future exploration

The MER mission has carried out the most far-reaching exploration of the surface of another planet in history. At Meridiani, Opportunity has discovered compelling evidence for an ancient aqueous environment that may have been suitable for some primitive forms of life. But to put the accomplishments of the rovers in perspective, they have traveled (as of July, 2005) a total distance of about ten kilometers on a geologically diverse planet that has as much surface area as all the landmasses of Earth combined. So there are many other places on Mars to be explored, and some future missions will surely be targeted to places significantly different from Meridiani Planum and Gusev Crater.

We argue, however, that when the time comes to return samples from Mars, Meridiani is a strong candidate site. Many outstanding questions of Meridiani's history could be solved by the detailed mineralogical analyses that would be possible with returned samples. And the detailed isotopic composition of the H, O, S, and even Fe known to exist in the rocks at Meridiani would provide extraordinary insights into Mars' environmental history.

Most significantly, Meridiani offers a chance not just to study an ancient habitable environment on Mars, but to search for evidence of former life there. Like many materials on the martian surface, the oxidized sedimentary rocks of Meridiani Planum are poor candidates for the long-term preservation of organic matter. However, the aqueous precipitates at Meridiani, most notably the hematite-rich concretions, might well retain a petrographic record of any microorganisms present at their time of formation. In addition, detailed isotopic analyses of Meridiani rocks have significant potential to reveal preserved biological signatures.

Meridiani is also a good place to land and operate a spacecraft, as the success of Opportunity has demonstrated. The regionally widespread distribution of sedimentary rocks at or just beneath the surface at Meridiani means that appropriate samples can be obtained there with limited roving or with shallow drilling. And the low winds, low elevation, equatorial latitude and smooth topography of Meridiani make it one of the safest and easiest places to land on Mars. We conclude that the rocks discovered by Opportunity are well suited, from both scientific and engineering perspectives, to addressing one of the most important questions in planetary science if the most advanced instrumental techniques can be brought to bear on them.

Acknowledgment

At the time of this writing (late July, 2005), Opportunity is in its 537rd sol on the martian surface, in excellent health and still exploring Meridiani Planum. Its performance and longevity are testimony to the efforts of a talented and dedicated army of engineers and scientists who made the MER mission possible. We owe them our deepest appreciation. We also thank in particular the other contributors to this special issue of *EPSL*, whose insights we have summarized here.

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