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An astrobiological perspective on Meridiani Planum

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Abstract

Sedimentary rocks exposed in the Meridiani Planum region of Mars record aqueous and eolian deposition in ancient dune and interdune playa-like environments that were arid, acidic, and oxidizing. On Earth, microbial populations have repeatedly adapted to low pH and both episodic and chronic water limitation, suggesting that, to a first approximation, the Meridiani plain may have been habitable during at least part of the interval when deposition and early diagenesis took place. On the other hand, the environmental conditions inferred for Meridiani deposition would have posed a challenge for prebiotic chemical reactions thought to have played a role in the origin of life on Earth. Orbital observations suggest that the combination of sulfate minerals and hematite found in Meridiani rocks may be unusual on the martian surface; however, there is reason to believe that acidity, aridity, and oxidizing conditions were broadly distributed on ancient Mars. When these conditions were established and how much environmental heterogeneity existed on early Mars remain to be determined. Because sulfates and iron oxides can preserve detailed geochemical records of environmental history as well as chemical, textural and microfossil signatures of biological activity, Meridiani Planum is an attractive candidate for Mars sample return.

Keywords: Mars; Meridiani Planum; Astrobiology; Environmental history; Microbiology

1. Introduction

Scientists (and many others) have speculated about martian biology for well over a century [1,2]. The new

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view of Mars offered in the 1970s by Mariner 9 and Viking did not resolve this debate, but profoundly changed its nature. For the first time, it became unambiguously clear that Mars shows nothing like the pervasive signatures that life has inscribed on the surface of Earth [3,4]. The present day martian surface is cold, dry, and chemically harsh, leaving subterranean oases as the most optimistic scenario for extant martian life. On the other hand, Mariner and Viking images of channels and possible ancient lake basins indicated that Mars may have been more hospitable to life early in its planetary history [5].

Debate about life on a young Mars sharpened with the publication by McKay et al. [6] of chemical, petrological and electron microscopic data from martian meteorite ALH84001, interpreted as evidence for biological activity in water-infused cracks within the early martian crust. Research over the past decade leaves these interpretations in doubt [7–11], but evidence for past surface water, bolstered in recent years by observations from the Mars Global Surveyor [12,13] and complemented by discoveries of layered rocks in many regions of the planet [14,15], still urges astrobiological investigation of early martian environments.

The first in situ characterization of sedimentary rocks by the rover Opportunity in Meridiani Planum [16,17] does not (once again) resolve the question of whether Mars ever supported life, but it does provide fresh perspectives on both habitability and biogenesis on the Red Planet.

2. Merdiani environment as inferred from opportunity data

The age of Meridiani outcrop rocks (informally christened the Burns formation) is only broadly constrained by crater abundances, but evidence detailed elsewhere [18] suggests that these rocks were deposited in late Noachian to early Hesperian times (ca. 4.0–3.0 Ga) in a setting physically analogous to terrestrial eolian systems characterized by alternating dune and wet interdune sedimentation [19]. In exposures examined inside Endurance crater, Burns strata can be subdivided into three units which form a sequence consistent with an upward increase in the influence of liquid water on sedimentation. Water lain, probably fluvial, sediments of the Burns upper unit lie above eolian sand sheet deposits of the Burns middle unit; these, in turn, overlie meter-scale, cross-bedded eolian sand dune facies of the lower unit. The sediments show strong evidence for pervasive aqueous cementation and diagenesis, even of eolian facies, indicating the presence, at least episodically, of saturated ground waters [20–22]. It is not clear whether surficial waters originated via ground water flow or regional landscape drainage, but the observed abundance of evaporite minerals through a stratigraphic section minimally 7 m thick indicates that water was present episodically for at least thousands of years, and possibly longer.

Meridiani outcrop mineralogy includes three major components [16,20,21]. By weight, 50–60% of the sediments are siliciclastic. Elemental abundances show that this component had a mafic source, although primary igneous minerals like olivine and pyroxene are absent or difficult to identify, suggesting significant alteration [21]. Another 30–40% consists of sulfate minerals, both as reworked clasts of impure evaporite and as cement. The remaining 10% is comprised of hematite, most conspicuously as 2–6 mm spheroidal concretions that occur throughout the outcrop [23–25]. The presence of jarosite in the sulfate component [23] is particularly noteworthy, as terrestrial occurrences of this mineral are associated with acidic environments, commonly 2–3 or lower [e.g., 26–27]. Eh/pH plots that specify varying conditions of composition and temperature indicate an upper pH limit of about 5.6 for jarosite precipitation [e.g., [28]]. This is illustrated in Fig. 1, an Eh/pH diagram showing relationships among iron minerals in equilibrium with an evolved brine derived from interaction with martian basaltic rocks, similar to that used by Tosca et al. [22] to model evaporation/diagenesis processes at Meridiani Planum.

The inference of potentially strong acidity during at least part of the history recorded by Meridiani rocks supports a class of environmental models for Mars championed by the late Roger Burns [26,29–31]; see [32] for a recent iteration]. It is also consistent with the absence of carbonate minerals in Meridiani sediments, and it provides a mechanism for iron diffusion through local ground waters (required for concretion growth) despite the absence of geochemical evidence for reducing conditions. It is not necessarily the case that iron oxides and jarosite co-precipitated in equilibrium with one another [22]. In the modern Rio Tinto, Spain, hydronium jarosite and other ferric iron sulfates form in highly acidic waters; however, these minerals dissolve and goethite precipitates downstream and during diagenesis, when pH rises to 4–5 [27]. The paragenetic sequence inferred from microscopic images of the Burns formation [24] is consistent with a hypothesis of sequential mineral precipitation and dissolution from chemically evolving ground waters [20,21]. Locally

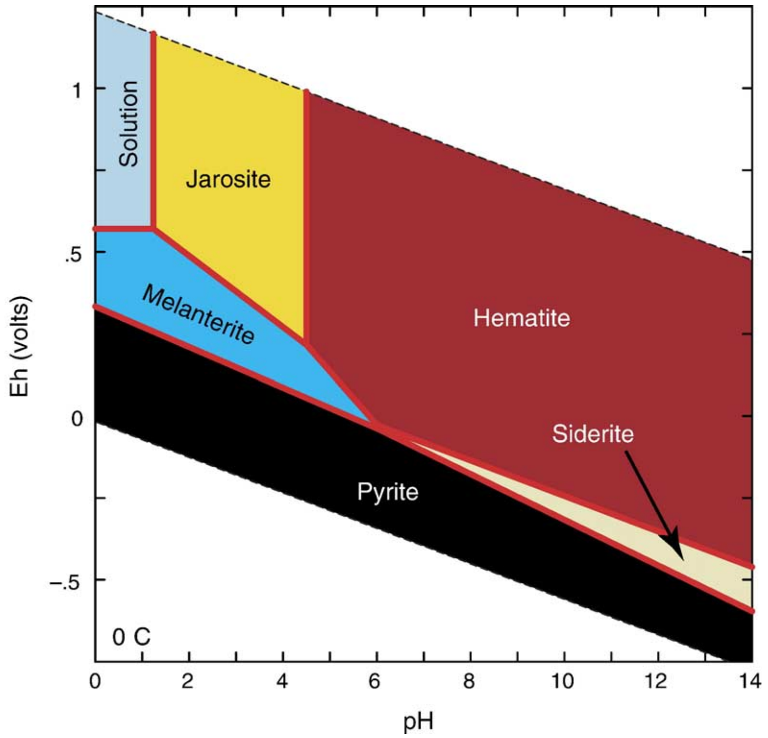

Fig. 1. Eh vs. pH diagram showing relationships among iron minerals in equilibrium with an evolved S-bearing brine and a CO_2-bearing atmosphere at $0°$ C and $P_T = 1.013$ bar. Conditions are as follows: $a H_2O = 10^0$; $a_{Fe_T} = 10^0$; $a_{SO_4^{2-}} = 10^{0.5}$; $a_K = 10^{-2}$; $a_{Na} = 10^{-2}$; $f_{CO_2}(g) = 10^{-1}$. Formation of goethite, bilinite, ferrohexahydrite and siderotil were suppressed. The mineral–thermodynamic data base is that used by Tosca et al. [22]. In this example the K-jarosite end member is used; Na-jarosite only becomes stable at very high Na/K ratios.

high concentrations of Br in Meridiani sediments suggest episodic evaporation to dryness [21].

3. The habitability of Meridiani environments

If the preceding summary is at least broadly correct, the ancient Meridiani plain experienced fluctuating environmental conditions which, at their extremes, would have presented two distinct challenges to habitability: aridity and acidity. We can elucidate these challenges by examining episodically dry and acidic environments on Earth.

3.1. Acidity and biology

Acidic environments where jarosite and other sulfate minerals precipitate in association with iron oxides occur in acid-mine drainage worldwide. The Rio Tinto river system in southwestern Spain has been well studied [e.g., [27] and references therein], and while it has been exacerbated by mining, this system is natural and includes diagenetically stabilized deposits up to two million years old [27]. Rio Tinto and other strongly acidic environments on Earth contain diverse microorganisms, including bacteria, archaea, and a surprisingly large variety of microbial eukaryotes [33–35]. (These acid drainage systems are not, in general, close *process* analogs of martian environments [27], but mineralogy and water chemistry suggest that they are informative as *state* analogs, the central issue in discussions of habitability). For most of these organisms, the molecular basis of acid tolerance remains unknown, although many bacteria and at least some acid-tolerant protists maintain cytoplasmic pH near neutrality, likely via membrane-embedded molecular pumps that export protons from cell interiors [34,36].

Microorganisms in acid mine drainage also tolerate high levels of potentially toxic metal ions [37,38], suggesting that this, as well, does not constitute an insurmountable barrier to biology. More problematic might be the availability of macronutrients. Nucleic acids, membranes, and proteins require nitrogen and phosphorus in biologically available forms, and it is likely that wherever life occurs, molecules that perform equivalent functions will make use of these elements. In Rio Tinto waters, fixed nitrogen and phosphates come mainly from surrounding terrestrial ecosystems, a regional supplement that, at best, may have been minimal on early Mars. Martian mafic rocks have relatively high phosphate contents, and under acidic conditions, apatite dissolution would be facilitated [39]. On the other hand, phosphate ions released by acidic weathering should become protonated, losing the negative charge that is key to their surface concentration [40]. Adsorption on the surfaces of precipitated iron oxides or hydroxides might also have limited the bioavailability of phosphate in Meridiani waters, although this process is pH dependent and would have been less significant under conditions of low pH [41].

Biologically usable nitrogen would have been supplied by nitrogen fixation, either by highly energetic physical processes such as lightning or by organisms. It has been hypothesized that N_2 abundances were much higher in the early martian atmosphere than they are today; if so, this Noachian nitrogen must either have escaped into space or become sequestered within the regolith as nitrates or ammonium salts [42,43]. (A parallel problem exists for CO_2, for which a postulated high early partial pressure contrasts with current atmospheric abundance [43]; as in the case of nitrogen, explanations for CO_2 decline involve loss to space or sequestration in a crustal reservoir yet to be identified). Empirical data on regolith nitrogen are lacking. At present, therefore, we don't know whether abiotically fixed nitrogen was readily available in early martian environments or whether soil reservoirs of fixed nitrogen have always have been small. Measurement of fixed nitrogen in martian regolith may indeed provide key data in arguments about Mars astrobiology and so should be a high priority for future missions [44].

At moderate pH, biological N-fixation could, in principle, provide the nitrogen needed to sustain microbial communities, but in strongly acidic waters the situation grows more complicated. Microbial communities in subterranean acid mine waters require local sources of fixed nitrogen, but to date, no one has observed biological N-fixation at low pH [33].

Assuming the availability of required nutrients, we must also consider primary production in acidic environments. We don't know whether ice was a prominent feature of the Meridiani depositional environment, but the existence of cyanobacteria and microalgae both within and beneath Antarctic sea ice [45] suggests that this would not have frustrated local photosynthesis. Nor would moderate acidity present a challenge for either photo or chemoautorophic microorganisms. In the harsh environments of acid mine drainage, Fe-based chemoautotrophs contribute to primary production and dominate it in the dark [46]; low pH does little to inhibit this metabolism, but it does require the sustained presence of a redox gradient so that microbes can exploit energetically the oxidation of Fe^{2+} to Fe^{3+}. In acidic environments, Fe^{2+} is produced rapidly by the weathering of mafic rocks, but it is oxidized relatively slowly, enhancing its availability for microbial metabolism [30]. H_2 produced by hydrothermal alteration of crustal rocks [47] and CH_4 (of unspecified origin) recently reported from Mars [48] provide further reduced substrates for chemosynthesis.

In contrast, photosynthesis dominates carbon fixation in acidic surface waters such as Rio Tinto [46]. Cyanobacterial genes have been identified in DNA extracts from Rio Tinto [46], but the metabolic importance of cyanobacteria in this ecosystem is likely to be low, as bacterial photosynthesis is strongly inhibited below pH 4 [49,50]. The reasons for this intolerance of low pH are unknown, but may relate to the requirement for a specific and sustained pH gradient across photosynthetic membranes [51]. In strongly acidic lakes and rivers, the principal photoautotrophs are eukaryotic algae that embed their chloroplasts within neutral cytoplasm, enabling these organelles to function in environments that were off-limits to their free-living cyanobacterial ancestors.

The limits imposed by pH on bacterial photosynthesis raise an interesting, if currently unresolvable issue about possible Meridiani ecology. Chemoautotrophy requires a redox gradient that can be exploited by microorganisms, and, more generally, the long term maintenance of ecosystems requires complementary metabolisms that cycle biologically important elements through oxidized and reduced reservoirs. Autotrophic metabolisms generate redox gradients via photo- or chemo-reduction of carbon dioxide, sulfates, ferric iron or other redox-sensitive chemical species. Thus, where autotrophs are present, environments have the potential to complete biogeochemical cycles. Chemoautotrophs, however, require the *prior* existence of redox gradients. H_2 or slowly oxidizing Fe^{2+} might have supplied reducing power, although oxidized Meridiani sediments suggest that these sources may have been limited. The existence of a redox gradient within waterlogged sediments at Meridiani Planum is not proscribed by available geochemical data, but neither is it supported. (The Fe^{3+} now resident in jarosite and hematite originated as Fe^{2+} in mafic minerals, requiring both oxidation and migration. In principle, this could have been accomplished either by oxidative chemical weathering and transport in acidic water or by anoxic weathering and transportation followed by oxidation). Absent the conditions necessary to promote chemosynthesis, the only source of fixed carbon (and, potentially, of reducing environments) would have been photoreduction by photosynthetic organisms. Thus, using terrestrial biology as a yardstick—and bearing in mind that any early Mars life would likely have resembled bacteria more closely than evolutionarily derived and cytologically complex algae, strong acidity could present a serious, albeit not necessarily fatal challenge to martian ecosystems.

3.2. Aridity and biology

On Earth, water activity constitutes a fundamental limit to life. A few fungi can tolerate water activities as low as 0.61, but for most organisms, biological activity ceases below a water activity of 0.90 [52]. Organisms that populate episodically or seasonally dry environments such as playas have biochemical means of tolerating low water activity. Many microorganisms can tolerate prolonged dryness, persisting as spores or as water-depleted, dormant cells protected by a capsule of glycoproteins around the desiccating cell [53].

Where evaporation is less complete, some organisms can grow and reproduce in brines, solving the physiological problem of osmoregulation by importing K^+ and Cl^- ions into the cell or by synthesizing so-called compatible solutes, organic osmoregulators that can accumulate to high concentrations in cytoplasm without disrupting the cell's biochemistry [54]. Indeed, some halotolerant microorganisms are actually restricted to highly saline environments, the high ionic concentrations in their cytoplasm precluding osmoregulation in fresh to normally saline ocean waters [54].

3.3. Meridiani as a habitable environment

As outlined in the preceding sections, biological responses to acidity and aridity are well known on Earth, but it is difficult to apply them in more than a general way to Meridiani Planum. (In gauging habitability by reference to environmental tolerances of terrestrial organisms, we do not mean to imply that life on Mars would necessarily conform to an Earth-like template. Life we know, however, provides our only empirical basis for thinking about life on other planets). The chief environmental variables are pH and the time scale of desiccation, neither of which can be determined with confidence from Opportunity's observations of Meridiani outcrop rocks.The principal biological variables are, in a sense, phylogenetic. On Earth, a variety of microorganisms tolerate high acidity and/or persistent water stress, but in most cases, the molecular mechanisms of physiological tolerance are *derived* — the microbial inhabitants of unusually acidic or dry environments are descended from populations that live in less stressful habitats [34].

Broadly, then, and bearing in mind the many outstanding uncertainties, terrestrial experience suggests that elements of a preexisting biota might well adapt to the environmental conditions inferred from Meridiani outcrop rocks—at least during those possibly short-lived intervals when liquid water was unambiguously present. That is, the local environment could, in principle, have been habitable at least transiently, at least when the "wetter" upper Burns units formed. This, however, leaves open the question of whether life could have gained a prior foothold on early Mars.

4. Could life have originated on Mars?

Could chemical evolution have proceeded in environments like those inferred from Meridiani outcrops? Most of the classic experiments in prebiotic chemistry have been run under at neutral to mildly alkaline pH for the simple reason that they work well under these conditions (e.g., [55]). Indeed, Russell [56,57] has argued that key prebiotic reactions on the early Earth took place along a chemical front between mildly acidic sea water and alkaline submarine seepages. Wächtershäuser [58] earlier advocated acidic vents as crucibles of chemical evolution, but his more recent experiments that demonstrate peptide formation via amino acid activation on metal sulfides were conducted at pH 7–10 [59].

Richly functionalized molecules hydrolyze readily under acidic conditions. For example, strong acids hydrolyze proteins and deactivate single strands of both RNA and DNA [60]. Moreover, at least three syntheses sometimes considered key to the origin of life are compromised by low pH: strecker synthesis of amino acids, HCN condensation to form purines, and the formose reaction to form sugars [55,61]. Sugar synthesis is doubly interesting because ribose and related pentose sugars can be stabilized by borate [62], but borate is an unlikely constituent of acidic environments.

Because they don't work well and are of limited relevance to Earth history, few chemical evolution experiments have been completed under acidic conditions. One example where a range of pHs has been considered is the classic template-directed polymerization of nucleic acids by Inoue and Orgel [63]. RNA oligomers synthesized under acidic conditions form non-functional triple helices rather than the biologically relevant double helices found at moderate pH [64].

Evaporative concentration or freezing of aqueous solutions at Meridiani would promote polymerization reactions required for chemical evolution [65]. And protonated phosphates produced under acidic conditions can condense to form soluble oligophosphates, facilitating phosphorylation of prebiotic molecules. Regardless of the chemical effects of acid and aridity, however, persistent oxidizing conditions may have precluded chemical evolution on the martian surface.

Of course, it is not necessarily the case that early Mars was everywhere and always acidic or oxidizing. Even within Meridiani sediments, ground water pH likely varied through time. And, as noted in the preceding section, hematite formation (possibly from goethite precursors) appears to have had a discrete temporal and geographic distribution. Beneath the hypothesized CO_2-rich atmosphere, Mars' early Noachian exterior might have been governed by a total CO_2 buffer [31,66], potentially obviating the problem of strong acid in prebiotic reactions. Recently, however, Fairen et al. [67] have argued that on early Mars iron would have buffered surface environments at pH below 6, regardless of carbon dioxide abundances. Consistent with this model, widespread surficial carbonates remain to be discovered on Mars [68], although carbonate minerals in fractures within martian meteorites [69] demonstrate at least local subsurface release from the hypothesized buffer.

There is much we don't know about the origin of life in general and even more that we don't know about chemical evolution in acidic environments. Opportunity's discoveries will undoubtedly inspire new experiments that may change our views of prebiotic chemistry across a range of conditions relevant to planets other than Earth. In continuing exploration, it will be important to establish when arid, acidic and oxidizing conditions were established on Mars. Likewise, it will be important to understand the environmental heterogeneity of early Mars, so that we might gauge the potential for prebiotic chemistry in subsurface or local surface environments even as acidic and oxidizing surfaces became widespread. It remains to be seen whether the Early Noachian martian surface was amenable to organic reactions; however, currently available data do not paint an optimistic picture of prebiotic chemistry in Meridiani-like environments of the later Noachian and afterward.

One more thought is worth consideration. It has been speculated that "we are all martians" — that life originated on Mars and spread to Earth via meteorites [70–74]. The emerging view that Earth and Mars parted environmental company early on suggests that despite the dynamic certainty that martian meteorites reached Earth from time to time, ecology could have presented an impediment to the success of any immigrant life. Indeed, given the potential obstacles to in situ martian biogenesis, any continuing speculation may well focus as much on the passage from Earth to Mars as it dos on immigration to our own planet.

5. Meridiani environments in planetary context

Broader considerations of martian astrobiology require that we understand how inferred Meridiani environments were distributed in time and space. According to TES mapping, surfaces containing 5–20% coarse grained hematite cover an area of at least 175,000 km^2 on Meridiani Planum [75,76]. Elsewhere, surfaces with more than a few percent coarse-grained hematite occur only in Aram Chaos and in small patches within Valles Marineris [75]. (The Meridiani hematite signal is pronounced because of crystal size and the accumulation of weathered out hematite spherules on the plain surface; finer grained and more dispersed sedimentary hematite may well be more widely distributed on the martian surface). However, a recent map of light-toned features interpreted as sedimentary rocks like those near Opportunity's landing site shows that these features cover a much wider area of Meridiani Planum than hematite-rich surfaces [[77], see also [78]]. New results from OMEGA corroborate this inference and, indeed, suggest that Mg-sulfates are widely distributed on Mars [79,80]. Thus, sedimentary rocks characterized by sulfates plus coarse-grained hematite appear to represent a geographically limited subset of all sulfate-rich sediments.

What factors might be responsible for the observed distribution of Meridiani-like sediments? Meridiani deposition required mafic parent rocks, a source of acidity, and water. Basalt was certainly not the factor that limited sediment distribution, as it surfaces most of the planet. Burns [26,29–31] hypothesized that sulfuric acid was generated on Mars by the oxidation of subsurface sulfides. If so, this could account for the regional distribution of the sulfate plus hematite rocks documented by Opportunity. The observed distribution of sulfate rocks, however, and a global dearth of surficial carbonates imply that sulfuric acid was more widely distributed across the ancient martian surface. H_2SO_4 formation by the reaction of volcanic gases with water vapor or products of the photolytic dissociation of H_2O [81,82] provides an alternative source of acidity capable of accounting for observed sediment distributions.

Banin et al. [83] have invoked acid volatiles to explain chemical properties of martian soil, inferring a relatively recent origin for soil salts, nanophase iron oxides and silicate mineraloids. Volcanogenic acid formation may well have continued at low rates through much of martian history, but it was likely most prominent when martian volcanism was most active. At Meridiani Planum, undisturbed (unRATed) sedimentary rock surfaces show Cl enrichment but sulfate abundances similar to or less than those of RATed (subsurface) samples, indicating that chemical alteration of outcrop exposures has been minimal on a billion year time scale [21]. Available data indicate that the essential geochemical features of Meridiani outcrop rocks are primary and ancient (formed during deposition and subsequent diagenesis), not secondary and recent (established since the formation of Eagle and Endurance craters) [20–22].

It is at least plausible that on a cold martian surface, sulfuric acid (melting point 285° K [84]) could have frozen out onto rocks and regolith rather than reacting immediately to form sulfate salts, thereby forming a potentially widespread reservoir of surficial acidity. Phase diagrams of H_2O–H_2SO_4 show eutectics where the melting point decreases by 40–80° K [85], potentiating the episodic generation of acidic surface or ground water even under conditions comparable to today's climate. Indeed, models by Marion [86] suggest that freezing can convert a weakly acidic aqueous $MgSO_4$ solution to one dominated by sulfuric acid.

If basalt and acid were distributed widely on ancient Mars, perhaps water was the factor directly responsible for regionalization of the martian hematite signature. On the total-CO_2-buffered Earth, reaction of basalt with abundant H_2O results in alkaline waters from which carbonate minerals precipitate. The extent to which these water–rock interactions would proceed on the early Mars surface depends on a number of factors, including pH buffering and the amount of water available. At high water–rock ratios, one might expect the chemical weathering of basalt to generate alkalinity in excess of acidity, resulting in the deposition of carbonate minerals. At the other extreme, minimally altered mafic rocks should be a persistent feature of the martian surface where the mean water–rock ratio is very low — or where ambient H_2O is frozen most of the time. Under intermediate, but still water limited, conditions, one might expect sulfate minerals to form, converting SO_2 and/or sulfuric acid to Fe, Mg, Ca, and other sulfate salts. As observed at Rio Tinto in Spain [27], continuing infusion by water should promote the dissolution of Fe-sulfates such as jarosite, with released Fe^{3+} redepositing as goethite that may, through continued contact with water, convert to hematite or, at low pH, hematite directly.

Such considerations suggest that martian sedimentary rocks rich either in little altered mafic clasts or in carbonate might form two end members of a lithological gradient controlled at least in part by water availability. In this view, sediments rich in iron sulfates, iron sulfates plus iron oxides, or iron oxides sans iron sulfates would be viewed as intermediates between these two extremes. Carbonates are, at best, a minor feature at the martian surface, suggesting that water–basalt interactions were insufficient to generate the alkalinity needed to titrate surface acidity, even regionally. In contrast, martian meteorites, orbital data, and in situ measurements all indicate the widespread presence of mafic rocks. (Hoefen et al. [87] have, in fact, argued that the persistence of olivine in Mars surface rocks reflects long-term water limitation. However, as olivine dissolves stoichiometrically in acidic waters [88], its identification on the present day martian surface does not by itself eliminate hypotheses that call for greater water availability in the past. As well, olivine could have been exposed by physical weathering processes that persisted long after the martian climate had become substantially drier. Regardless, the observation stands that mafic rocks are common on the martian surface whereas carbonates are not known to be widespread).

Jarosite and hematite in combination are known with certainty only in Meridiani Planum, although the two might co-occur elsewhere, for example in Aram Chaos and in small patches within Valles Marineris, where hematite has been identified by THEMIS. As prolonged reaction at high water/rock ratios would be expected to result in jarosite (especially hydronium jarosite) dissolution, with iron re-precipitated as iron oxide or hydroxide, rocks containing both jarosite and hematite likely formed under conditions of water limitation [[89], see also [27]] As noted above, OMEGA's recent discoveries indicate a much wider distribution of sulfate minerals sans identifiable hematite. Such sediments could have formed under conditions of differing pH, greater water limitation, or both.

Thus, the martian surface may contain the suite of minerals/lithologies expected along the water-limited portion of the proposed basalt–carbonate spectrum. If this view is even broadly correct, it suggests that the feature that distinguished Meridiani from other regions of Mars was neither mafic source rocks nor acid, but water. During the interval when the Burns formation accumulated, water-cut channels and perhaps even oceans may have existed on Mars [3–5]; Meridiani mineralogy forces us to consider whether the liquid water required for such features might have been intermittent or very cold [90].

6. Meridiani Planum and astrobiological sample return

Speculation about extraterrestrial life is easy, but as André Gide [91] wrote many years ago, "Fiction is history which might have taken place." Many scenarios for extraterrestrial life are plausible, but sorting astrobiological fact from fiction will require a sustained program of observation and exploration. On Earth, biological and environmental signatures are well preserved in sedimentary rocks. Evidence such as macroscopic textural features, microscopic fossils, and organic and isotopic geochemical indicators show that Earth has been a biological planet for most of its history [92]. Sedimentary rocks on Mars can be investigated in comparable ways.

Of the various biosignatures known from Precambrian rocks on Earth, only macroscopic sedimentary textures imparted by microbial communities – biogenic stromatolites, wrinkle structures, "manes" of mineral encrusted filament populations – could, in principle, be detected by Opportunity's instrument package. To date, no such features have been observed. Indeed, all sedimentary structures imaged by Opportunity thus far find ready explanation in terms of physical/chemical processes acting alone.

This does not rule out biological activity in the ancient Meridiani basin — microscopic and biogeochemical signatures of life can be found in many Precambrian terrestrial rocks that do not preserve macroscopic textural biosignatures. It does, however, suggest that definitive answers to astrobiological questions will almost undoubtedly require sample return. Given our current understanding of the martian surface, the concretion-bearing evaporitic playa deposits of Meridiani Planum must qualify as a high priority target for sample return a decade from now. Microfossils can be preserved in sulfate precipitates [93], and cellular preservation in iron oxides – including preservation of bacterial cells – can be spectacular. For example, at Rio Tinto, goethite and hematite in Pleistocene and Holocene terraces preserve bacterial, microalgal and fungal microfossils that are easily differentiated from non-biological fabrics in the same rocks [27]. Any microorganisms present in the Meridiani environment might well have left a morphological record in sulfate cements or hematitic concretions, but it will take high resolution optical and electron microscopy to test this possibility. Organic matter rarely preserves well in oxidizing, Fe^{3+}-rich environments [94], but can come in contact with salt-rich sediments via diagenetic hydrocarbon migration [95]. Of course, regardless of how the search for biosignatures ends, detailed textural and geochemical analyses of Meridiani evaporites will greatly sharpen our sense of Mars' environmental history.

Outcrop is discontinuously exposed on the Meridiani Plain, but it appears to be everywhere close to the surface. The MER mission demonstrated that a rover with a range of just hundreds of meters can provide access to outcrop rock in this region; so far, Opportunity has encountered exposed outcrop at four different locations (Eagle crater, the Anatolia fractures, Fram crater and Endurance crater) over a traverse of less than 1 km [17]. Thus, moderate-accuracy landing coupled with rover-based sample collection would provide one possible means of obtaining such materials. MER results also show that rock is present under a thin (1–2 m) cover of wind-blown sand over much of the Meridiani region, suggesting that sample collection via shallow drilling may be possible as well.

Opportunity's discoveries on Meridiani Planum hand astrobiologists half a glass of water. Local environments may well have been habitable during at least part of the interval when Meridiani outcrop rocks formed. On the other hand, Meridiani sedimentary rocks support models of martian environmental history that that might have frustrated prebiotic chemistry. Only continuing exploration will tell us whether the figurative "glass of martian water" is half full or half empty.

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