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Research Article

Oceans, Lakes, and Stromatolites on Mars

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Billions of years ago, the Northern Hemisphere of Mars may have been covered by at least one ocean and thousands of lakes and rivers. These findings, based initially on telescopic observations and images by the Mariner and Viking missions, led investigators to hypothesize that stromatolite fashioning cyanobacteria may have proliferated in the surface waters, and life may have been successfully transferred between Earth and Mars via tons of debris ejected into the space following bolide impact. Studies conducted by NASA's robotic rovers also indicate that Mars was wet and habitable and may have been inhabited in the ancient past. It has been hypothesized that Mars subsequently lost its magnetic field, oceans, and atmosphere when bolides negatively impacted its geodynamo and that the remnants of the Martian seas began to evaporate and became frozen beneath the surface. As reviewed here, twenty-five investigators have published evidence of Martian sedimentary structures that resemble microbial mats and stromatolites, which may have been constructed billions of years ago on ancient lake shores and in receding bodies of water, although if these formations are abiotic or biotic is unknown. These findings parallel the construction of the first stromatolites on Earth. The evidence reviewed here does not prove but supports the hypothesis that ancient Mars had oceans (as well as lakes) and was habitable and inhabited, and life may have been transferred between Earth and Mars billions of years ago due to powerful solar winds and life-bearing ejecta propelled into the space following the bolide impact.

1. The Oceans, Lakes, and Search for Stromatolites on Mars

In 1784, 1882, and 1895, and based on ground-based telescopic observations, several prominent astronomers suggested that Mars may have had oceans and rivers [1–3]; a hypothesis later supported by evidence was provided by the Mariner, Viking, and Mars Global Surveyor missions [4–10]. These findings led to suggestions, beginning in the 1970s, that water-dwelling algae (cyanobacteria) may have constructed stromatolites on the Red Planet [9, 11, 12] and that a "search for stromatolites on Mars" should be undertaken [13]. In 2002, DiGregorio reported what he believed to be biosignatures compatible with stromatolite-building cyanobacteria in an ancient paleolake; a hypothesis was based on the detailed analysis of images from the Viking landers photographed at Utopia Planitia and Chryse Planitia. Subsequent orbital observations and ground level studies conducted by NASA's Mars rovers [14–20] also indicate that water repeatedly flowed and pooled upon the surface [21–26], possibly providing a habitable environment billions of years ago [16, 27–31]; a time period which coincides with the fashioning, 3.7 bya, of what may be the first stromatolites on Earth [32, 33] and Mars was reported by Noffke [34]. Specifically, Noffke [34] reported the discovery of what appear to be Martian stromatolites, constructed 3.7 bya, in a receding body of water; a finding was consistent with the observations of other investigative teams who have observed Martian sedimentary structures that resemble stromatolites that may have been fashioned in ancient paleolakes and ocean shorelines [34–43]. Many of these putative Martian stromatolites are domical and concentric in shape [38] similar to those of Lake Thetis in Western Australia (Figures 1–4) which is 2 kilometers from the Indian Ocean.

If Mars had an ocean, or if there was one ocean or two, is largely based on observations of a smooth flat lowland basin circling the Northern Hemisphere bordered by rugged highlands in the Southern Hemisphere [5, 7, 8, 44]. There is also evidence of hundreds of paleolakes and paleoshorelines in the northern lowlands [4, 45–48] and evidence of catastrophic floods [47, 49] and prograding channels, which suggest rapidly receding bodies of water [15]. The overall pattern of geologic evidence, particularly the valley networks that abound in the Noachian highlands and the fluvial and erosion pathways, is indictive of Noachian ocean [50].

2. Bolide Impact, the Martian Geodynamo, and the Waters of Mars

What became of the oceans and lakes of Mars is unknown. It is believed they may have become periodically frozen [8, 47, 51–53] or assimilated as ice sheets beneath the surface and deep within the crust [8, 54, 55], a consequence, perhaps, of the slowing and stoppage of its "geodynamo" and loss of its magnetic field around 3.7 bya (Acuña et al. [10, 56]), though the actual cause and date are unknown. It has been hypothesized that massive and repeated bolide impacts may have impacted that "geodynamo" [57], thereby, causing a substantial reduction in the planet's heat flow, resulting in cooling and aridification of the climate and the loss of the magnetic shield followed by the loss of atmosphere due to powerful solar winds and UV rays [58–61]. Hence, the waters of Mars may have become frozen, and these sheets of water-ice were subsequently buried by debris [8, 51, 54, 55]. Periodically, however, some of these underground reservoirs of water may percolate to the surface and saturate the atmosphere during the warmer summer months [62–64]. There is no consensus, however, and it is unknown if an ocean of water covered the Northern Hemisphere only to be replaced by lakes or if oceans and lakes coexisted, which in turn evaporated and/or seeped beneath the surface [49].

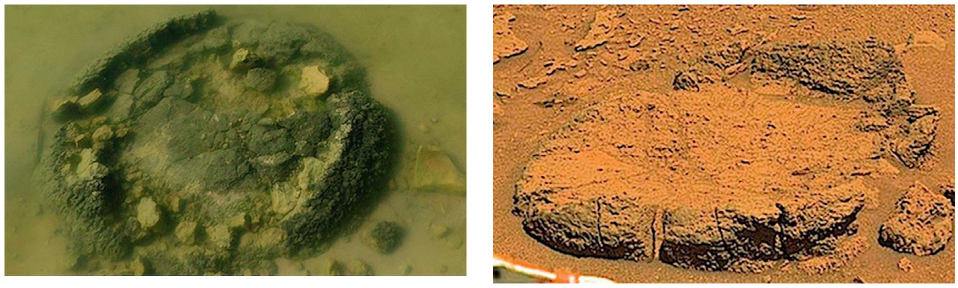
3. The Martian Solar Habitable Zone

That ancient Mars was wet and habitable has been documented by NASA's robotic rovers [16, 28]. Also consistent with habitability are the presence of organics and sufficient sunlight, which could provide energy to innumerable organisms [65–67]. The ancient geochemical environment of Mars would have also provided a chemolithoautotrophic energy source [16, 68, 69]. In fact, all the necessary elements for life (i.e., C, H, N, O, P, and S) have been detected [70, 71].

The existence of liquid surface water on ancient Mars, as on Earth, is also evidence of habitability [72]. The habitable zone of a stellar system is usually defined as a circumstellar belt, inside which water can be maintained in the liquid state on the surface of a terrestrial planet orbiting that star, thereby, creating conditions favorable to life [73–75], i.e., referred to as the "*Temperate Zone of the Solar System*" [72]. Taking into account the influence of solar luminosity and irradiance on surface planetary temperatures [76–78], it has been estimated that the inner and outer edges of the habitable zone of the solar system are located within 0.836 and 1.656 AU from the sun [79], though the exact parameters have yet to be determined. Mars has an orbit with a semimajor axis of 1.524 AU and an eccentricity of 0.0934 AU [80], which means that the Red Planet orbits within the habitable zone.

The width of the continuously habitable zone since the formation of the solar system, 4.6 billion years ago, has been estimated as between 0.95 and 1.15 AU [74, 81, 82]. If Mars had a less eccentric orbit billions of years ago and/or prior to whatever cataclysm may have negatively affected its "geodynamo" is unknown. Nevertheless, even with an axis of 1.524 AU and an eccentricity of 0.0934 AU [80], the Red Planet would have orbited within the habitable zone for much of the year, conditions which may also help explain the evidence of catastrophic flooding and what may be the receding and freezing of Martian oceans and lakes, i.e., a freeze-thaw cycle due to the eccentric orbit. And yet, the early atmosphere of Mars was probably much denser than at present (1.3–4 bar) and composed of CO_2 and H_2O in addition to 5–20% H_2 [83–85], and these gasses could have created a greenhouse effect and raised the mean annual and global surface temperature above the freezing point of water [83, 86]. As summed up by Ramirez [87], "Although most investigators believe that the geology indicates the presence of surface water, disagreement has persisted regarding how warm and wet the surface must have been and how long such conditions may have existed. The geologic evidence is most easily explained by a persistently warm climate. Requiring only ~1% H_2 and 3 bar CO_2 or ~20% H_2 and 0.55 bar CO_2. Such that a warm and semi-arid climate remains the simplest and most logical solution to Mars paleoclimate."

Hence, although the sun may have been 20–25% weaker [88], ancient Mars—like ancient Earth—due to its position in the circumstellar habitable zone, coupled with the presence of water on the surface and the composition of its CO_2-rich atmosphere, would have been warm, wet, and habitable over 3 billion years ago [16, 61, 89–91]. A warm, wet Mars with lakes and possibly oceans upon the surface would account for the observations of twenty-five investigators who have provided evidence of Martian sedimentary structures that resemble fossilized stromatolites fashioned by cyanobacteria in ancient lakes and shorelines [35, 37–40, 42, 43], at least one of which may



(a) (b)

Figure 1: (a) Lake Thetis under water stromatolite (permission to reproduce photo granted by Lyn Lindfield and The-TravellingLindfields.com). (b) Sol 529: Martian specimen with evidence of concentric lamination and fossilized fenestrae (reproduced with permission from [38]).

have been constructed 3.7 bya [34], and thus, at the same time, stromatolites may have been the first formed on Earth [32, 33].

4. Stromatolites

The formation, growth, and structure of laminated cyanobacterial mats and their calcification and photosynthetic properties have been described in detail by previous workers [92–94]. Cyanobacteria are often assisted or accompanied by other microbes including sulfate reducing and purple bacteria, which form bacterial communities that collectively precipitate $CaCO_3$ in shallow waters, which in turn enables them to cement together sedimentary structures [93, 95, 96]. As cyanobacteria also produce oxygen as a photosynthetic byproduct, fenestra and apertures are commonly formed in the matrix by gas bubbles; and features similar to these (Figures 5 and 6) have been observed within or adjacent to stromatolite- and bacterial mat-like formations on Mars [34, 38, 41, 42].

Stromatolites may take the form of stratified and layered mounds, columns, and sheet-like sediments that are conical, domal, stratiform, or branching—and similar sedimentary structures have been observed on Mars [38, 97]. These sediments are usually cemented together via the mucous and biofilm secretions and intertwined filaments and tendrils of cyanobacteria that bind together sand and sedimentary grains [94, 98–102].

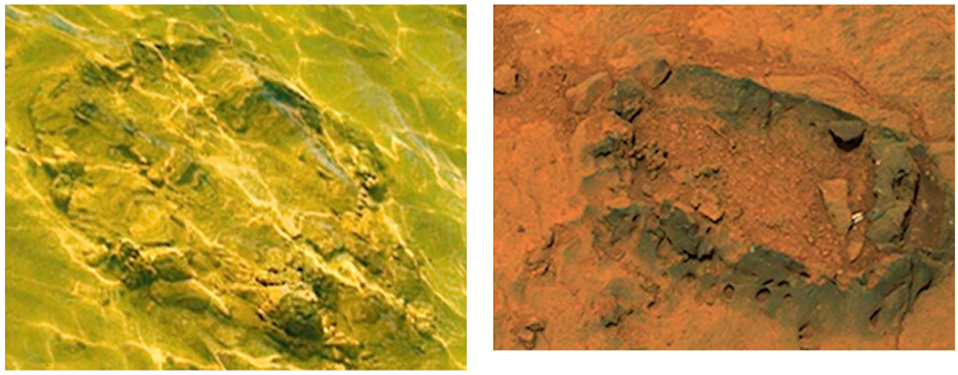
Stromatolites are also constructed by lichens, via the alga photobiont of the lichen symbiotic consortium; and these sediments are generally formed above water, atop rocks inhabited by endolithic lichens [103, 104], and specimens resembling endolithic lichens have been observed in the paleolake beds of Eagle and Gale Crater [38, 105]. By contrast, those typically fashioned by cyanobacteria are formed along shorelines and shallow waters [106, 107]. As algae and stromatolite-building lichens are photosynthesizing organisms, deriving their energy via sunlight [104, 108–110], water-dwellers colonize sediments and orient and clump together and on top of each other forming layers and growing towards the light [94, 103, 111, 112], thus forming sedimentary structures that rise above the water; and formations resembling those formed in shallow waters have been observed on Mars [34, 35, 38, 40, 42, 113].

A similar pattern of cementation and construction is also a characteristic of thrombolites [98–101]. Thrombolites are thick microbial mats [106] consisting of calcified cyanobacteria sheaths [107, 114–116] and which are cemented together via the precipitation of carbonate minerals within the mucilage [93]. These photosynthesizing microbes migrate toward the sunlight, thereby, forming layers of microbial mats [98–101]. Fossilized thrombolites/bacterial mats have also been observed on Mars [34, 38, 41, 42].

On Earth, the first evidence of stromatolites has been dated to 3.7 bya [32, 33]—though not all investigators accept these dates. However, stromatolites and thrombolites continue to be fashioned in the present day, having been found along sea shores and reefs, fresh water lakes [117, 118], and in lagoons and hypersaline lakes [119–122]. Lake Thetis and other Western Australian lakes are hosts to fossilized and living domical conical stromatolites and thrombolites [112] and are believed to be analogs to Martian paleolakes lakes [123, 124] and the lakes of Gale Crater [38]. Specimens resembling and nearly identical to the concentric domical stromatolites of Lake Thetis have also been tentatively identified in the dried lake beds of Gale Crater [38, 113].

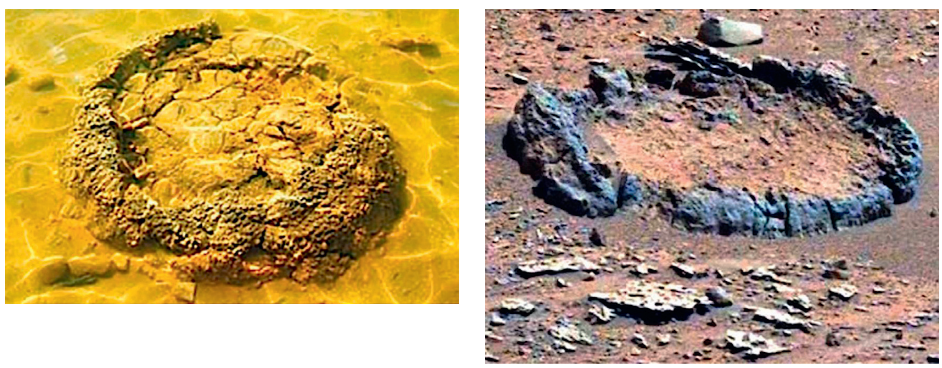
5. Lakes in Gale Crater

Most investigators directly involved in the exploration of Gale Crater by the rover Curiosity agree that this area was habitable early in the history of Mars and was flush with water, rivers, streams, and lakes [125–127]. Gale Crater is marked by numerous fluvial valleys, gullies, and water pathways [58, 128–130] and has all the characteristics of a series of dried lakes [16] that may be periodically replenished with water [20]. Based on morphological observations, Fairen et al. [58] described what they believed to be "evidence for ancient glacial, periglacial and fluvial (including glacio-fluvial) activity within Gale crater, and the former presence of ground ice and lakes." However, Grotzinger et al. [125] did not find periglacial evidence. Based on morphology, Oehler [130] argued that landforms indicate a "major history of water and ice in Gale crater, involving



(a) (b)

Figure 2: (a) The remains of a Lake Thetis underwater stromatolite. Photo credit: government of Western Australia department of mines and petroleum. (b) Sol 308 water pathways leading down and curving around a Martian specimen resembling a Lake Thetis stromatolite. Reproduced with permission from [38].



(a) (b)

Figure 3: (a) Submerged Lake Thetis stromatolite. Photo credit: government of Western Australia department of mines and petroleum. (b) Sol 122: Martian specimen with collapsed dome and evidence of fossilized fenestrae within the upper portion of the walls. This specimen appears to be fossilized and displays the vertical and inward orientation typically caused by upward-migrating microbial colonies at the sediment-water interface (Figure 4). Several "peanut-brittle" specimens resembling thrombolite mats appear in the bottom portion of the photo.

permafrost, freeze-thaw cycles, and perhaps ponded surface water." Masson et al. [131] have come to similar conclusions.

There are gullies, water pathways, and deltas which are most likely formed following heavy rains or the melting of ice and snow which released rivers of water, which often flowed from north to south and deposited sediment in the numerous lakes on the crater floor [20, 125]. These lakes may have periodically dried out, only to be replenished [63], in a cycle that may have lasted billions of years [132–135]. Water may have continued to flow into and perhaps partially filling the Gale Crater lakes, thereby replenishing the water supply repeatedly, until 145 million to a few million years ago. As summed up by Rampe et al. [20], "Evidence for a long-lived lake or lake system in Gale crater is compelling "possibly" up to the present day."

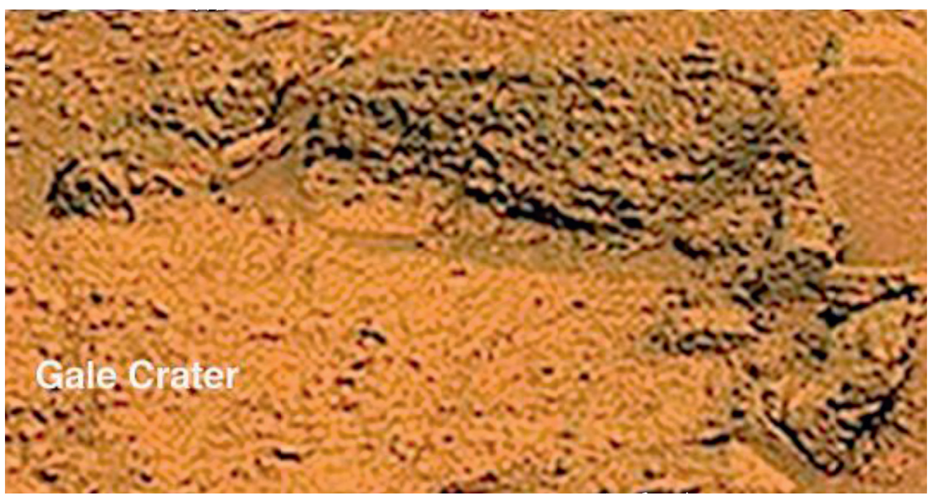
That those waters were leached from rocks, melting subsurface ice sheets, percolating upward from underground aquifers, and raining down upon the surface is also evidenced by the numerous fluvial gullies and pathways, which appear to have been fashioned by flowing liquid across the surface of Mars ([136, 137]). For example, as detected by the rover Curiosity's suite of sampling instruments, clays, mudstones, and a variety of minerals have been repeatedly hydrated [16, 27, 68, 125, 138, 139]. Therefore, Gale Crater appears to have undergone mineralization due to the presence of large amounts of water [128] and has likely repeatedly filled with water [58, 140–146].

At a minimum, therefore, the evidence indicates that ground and subsurface water may have been continuously or at least intermittently present beginning around 3.8–3.6 bya and continuing for the following 1.5 billion years [20, 26, 63, 147] and intermittently thereafter. Gale Crater therefore provided a habitable environment [16, 125]. Moreover, that environment may have been colonized by photosynthesizing cyanobacteria 3.7 bya [34].

6. Stromatolites in Gale Crater

If the waters and lakes that continuously or periodically filled Gale Crater were alkaline or saline is unknown, though it has been argued, based on an analysis of hydrated minerals, that

(a)



(b)

(c)

FIGURE 4: (a) Gale crater/sol 528 (close up of sol 122 (Figure 3). (b) Close up of sol 529. *Note*. Features resembling apertures, open cone-like structures, gas domes, and fenestrae. These gale crater specimens may be hundreds, thousands, or hundreds of thousands of years in age. Both appears to be fossilized and weathered. Contrast with (c) Lake Thetis living stromatolite photographed beneath the water and featuring numerous gas domes, apertures, and fenestra.

these lakes were more alkaline than saline and similar to the lakes of Western Australia [110, 123, 124], Lake Thetis in particular [38], although if one or more of these lakes were saline or hyposaline is also a possibility [148].

Consistent with the evidence of repeated episodes of hydration followed by drying, Noffke [34] has found evidence of microbial mats in the Gale Crater, which may have formed 3.7 bya in regressive bodies of water. Specifically, Noffke [34] reported that these mats have the microstructure and morphologies and stratigraphic successions typically produced by colonies of microorganisms, i.e., “centimeter-to meter-scale structures similar in macroscopic morphology” that include “mat chips,” “erosional remnants and pockets,” “desiccation cracks,” “roll-ups,” and “gas domes” that are arranged in spatial and temporal successions similar to the “growth of a microbially dominated ecosystem that thrived in pools that later dried completely.”

The microstructure of a putative Martian stromatolite photographed in the Gale Crater (Sol 506) was also found to be comparable to a terrestrial stromatolite from Lagoa Salgada, Brazil [37]. Highly organized microspherules, thrombolytic microfacies, voids, fenestrae, intertwined filaments, and layer deformation were common to both (Figures 4, 5, and 7).

In 2019, a team of 14 experts conducted an extensive search of NASA’s rover Curiosity Gale Crater image depository for macrostructures, which resemble the stromatolites of Lake Thetis, and subsequently, published pictorial evidence of six concentric domical specimens, four of which are nearly identical to those of Lake Thetis [38]. Two specimens were photographed adjacent to features which resemble thrombolite bacterial mats, and a third concentric dominical formations was determined to consist of five layers of crinkly and wavy nodular laminae with several orders of curvature, an abundance of detrital material, the presence of what appears to be numerous fenestrae/gas bubbles, a central (albeit collapsed) axial zone, and features that resemble the preferential vertical, upward, and inward growth, which is typically caused by upward-migrating microbial colonies at the sediment-water interface [112, 121, 122]. Moreover, extensive nodular biological mats and thrombolites were identified on and adjacent to this specimen (Figures 40–43 in [38]), thereby, fulfilling the criteria for a biological vs. an abiogenic formation [149–152]. Rizzo [97], in a work published by the International Journal of Astrobiology, replicated some of the findings of Joseph et al. [38] and also found evidence of fenestrae and what may be fossilized algae.

A common attribute of stromatolite-like formations observed in Gale Crater is the presence of open apertures, fenestrae, and what appear to be gas domes [34, 38, 97]. Open cone-shaped apertures were also observed adjacent to formations resembling algae and lichens [38]; though if these latter specimens are alive, fossilized, or abiotic is unknown. On Earth, gas domes similar to those observed on Gale Crater (Figures 4–7) serve to vent oxygen and other gasses produced during photosynthesis [153, 154]. Therefore, it could be argued that these open apertures and fenestrae were produced via venting of oxygen produced by photosynthesis. This evidence is consistent with orbital and ground level studies indicating that Gale Crater was home to numerous lakes and supports the hypothesis put forth by numerous investigators in the last century that stromatolites may have been fashioned in the paleolakes of the Red Planet. Moreover, formations resembling stromatolites have been observed in other areas of the Northern Hemisphere of Mars.

7. Stromatolites and Gusev Crater Lake

Gusev Crater may have been an ancient ice covered lake, which was fed by aquifers and subject to flooding from surrounding areas, and this watery environment may have persisted from 4.6 bya to 3.5 bya [155] followed by episodes of filing, evaporation, and drying until about 2 bya [156]. Subsequent analyses by the rover Spirit’s suite of instruments found evidence of an “unequivocal interaction” between water and the rocks in the Gusev plains [157], and it was hypothesized that rain, ice, and snow have been repeatedly produced by precipitation and condensation from the atmosphere [158]. Melting of ice from beneath the surface may have also repeatedly covered the surface with water [159].

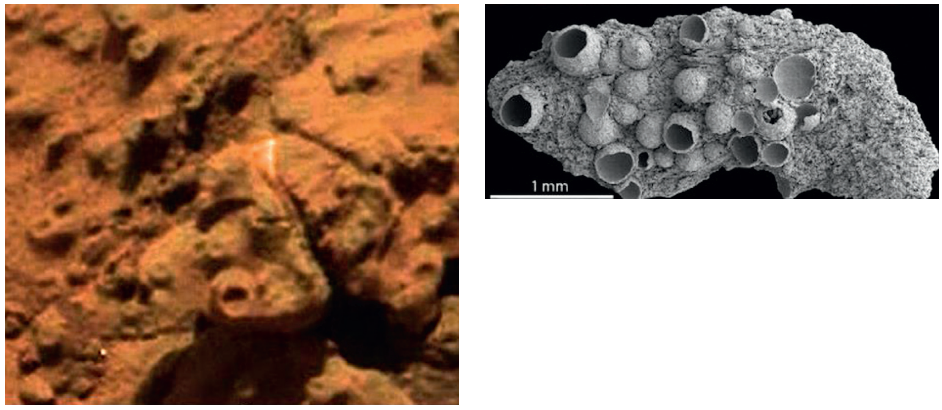
Analyses of surface rocks and regolith at Gusev Crater and the adjacent Columbia Hills indicate obvious evidence of water erosion, ranging from mild to severe [157, 160–164]. Although no current evidence of moisture, ice, or snow has been detected, it has been concluded that “Gusev Crater” may have been conducive to life on Mars in the past [165].

Gusev Crater, therefore, was an ancient habitable lake, which may have been filled or periodically filled with water from 4.6 to 3 billion years ago [156]. Those living creatures which may have dwelled in the lake may have also included stromatolite-building cyanobacteria [40].

Ruff and Farmer [40] reported evidence of what appear to be “microbially mediated micro-stromatolites” photographed by the rover Spirit. They detected biofilms, sheaths, and microstructures organized as intertwined microspherule filaments. Additional morphological analyses of sedimentary specimens resembling Gusev Crater stromatolites have also revealed microstructures organized as intertwined microspherule filaments nearly identical to those observed in Earthly microbialites [41, 42]. Like the stromatolites observed in Gale Crater, Rizzo and Cantasano [41, 42] also detected evidence of gas domes within these putatative Gusev microbialites similar to those fashioned by cyanobacteria for the venting of oxygen produced via photosynthesis. If these are in fact stromatolites, it is likely they may have been constructed over 3 billion years ago when Gusev Crater was a lake filed with water.

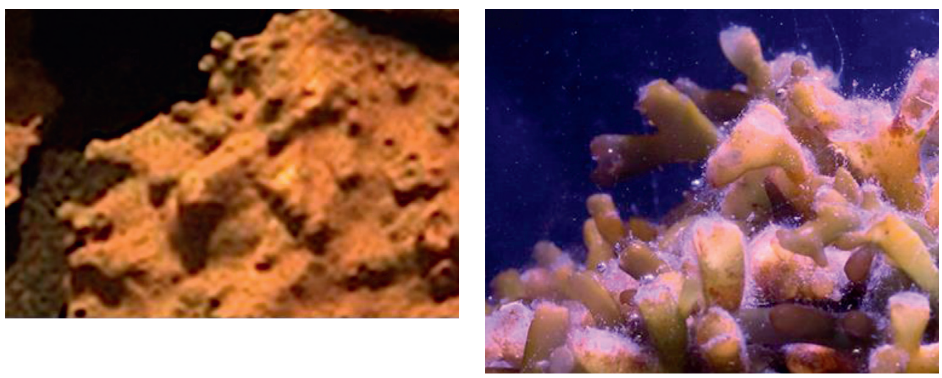
8. Meridiani Planum, Water, and Stromatolites

Investigation of Meridiani Planum soil and regolith, via the rover opportunities suite of sampling instruments, also detected considerable evidence that sediments had been deposited by flowing water [166]. The observation of sand ripples, centimeter scale cross-stratification, and festoon geometry of cross-lamination of surface features has also



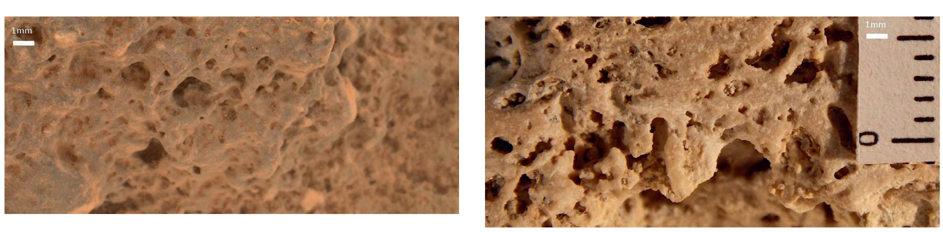
(a) (b)

Figure 5: Gale crater/sol 232. (a) Specimens similar to open cone and gas-vent apertures formed via the release of oxygen secondary to photosynthesis. Photosynthesizing organisms respire oxygen and release gas bubbles into the surrounding matrix, thereby, fashioning these vents. Surrounding green substance may be algae/cyanobacteria ([38]; reproduced with permission). (b) Open globular structures, interpreted as formed by gas bubbles via cyanobacteria oxygen respiration within microbial mats ([153]; reproduced with permission).



(a) (b)

Figure 6: Sol 232 (a): cone-like formations that resemble gas-vent apertures for the release of oxygen secondary to photosynthesis by algae/cyanobacteria and which appear to be moist. If they are alive, fossilized, or abiotic is unknown. (b) Cone-like tubes for the venting of oxygen produced by photosynthesizing water-dwelling algae (reproduced with permission from [31]).



(a) (b)

Figure 7: Microanalyses of a Martian stromatolite-like formation (a) photographed by the rover curiosity (sol 506) in gale crater compared with (b) a terrestrial stromatolite from Lagoa Salgada, Brazil. Voids, apertures, and highly organized microspherules and thrombolytic microfacies are common to both. Earthly cyanobacteria typically form voids, intertwined filaments, and layer deformation within stromatolites (reproduced with permission from [37]).

been interpreted as due to the flow of water [18, 28]. Likewise, the presence of channels indicates that water from melting snow and "massive ice deposits" [138, 167] may have flowed downward into local basins forming numerous pools of standing water [168] between dunes of sand and which saturated the soil [169]. There have been repeated episodes of ground water inundation in Meridiani Planum [170]. Moreover, it appears that pools of water were formed from the upwelling of underground aquifers followed by evaporation, and that global groundwater flow may have been driven by precipitation [140, 171]. Thus, there is considerable evidence for the flow and pooling of a significant amount of ground water at various times in the history of Meridiani Planum, including the possible formation of transient lakes in Endurance Crater [29, 172].

Squyers and Knoll [169] in summing of the data from Meridiani Planum have argued that there is "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."

Rizzo and Cantasano were the first to identify possible stromatolites/microbialites on Mars and performed a detailed microanalysis of this structure located in what they believed to be an ancient lake bed within Meridiani Planum. They observed and provided evidence of segmented sedimentary structures bordered by lamina similar to microbialites on Earth [41, 42]. Bianciardi, Rizzo, and Cantasano [35, 42] performed a detailed statistical, comparative, quantitative analysis of these stromatolite microstructures and which they compared to terrestrial stromatolites and microbialites. These scientists found microdomes, fenestrae, and extensive morphometric similarities in texture and organization almost identical to stromatolites constructed by cyanobacteria/algae.

In addition, formations resembling fossilized algae have been identified by Kaźmierczak [173] along the shoreline of Endurance Crater, which billions of years ago is believed to be one of the many lakes in Meridiani Planum [29].

Water-dwelling-rock colonizing lichens also construct stromatolites [103, 104], and thousands of mushroom-shaped lichen-like formations have been also been observed in Meridiani Planum, within Eagle Crater [105], which some investigators believe may have been small lake [169]. These lichen-like formations form vast colonies and are attached to rocks by thin stems and oriented skyward similar to photosynthesizing organisms. If these lichen-like specimens are abiotic, living, or fossilized is unknown.

9. The Waters of Utopia and Chryse Planitia

The Viking Landers touched down at Utopia Planitia and Chryse Planitia, in 1976. Condensation and sublimation of ground frost was observed [174], and water within regolith was a detected via Viking's mass spectrometers [175]. The presence of frost and water indicates that Utopia and Chryse Planitia could provide a habitable environment for extremophiles adapted to extremely cold environments, including fungi, lichens, and a variety of archae and bacteria. Utopia and Chryse Planitia are also believed to be ancient paleolakes [142] and may have and may still provide a habitable environment for algae [176].

DiGregorio [177], upon examining the 1976 Mars Viking images, observed what he interpreted to be "rock varnish" typically produced by a wide variety of microorganisms "including epilithic and endolithic cyanobacteria." DiGregorio hypothesized that cyanobacteria may have cemented sediments together, fashioning microbial mats and stromatolites in these ancient Martian lakes.

10. Early Life on Earth: Parallels with Mars

Although considered controversial [178, 179], evidence of biological residue, carbonates, chains of magnetite, and fossilized polycyclic aromatic hydrocarbons (PAHs) have been discovered in ALH 84001 [12, 180, 181]. It has been argued that at least 25% of the organic residue is biological [30] and can be dated to at least 3.8 bya to 4.2 bya [30, 182].

Prior to ejection into the space, ALH likely originated in a watery environment [30, 183] and was subject to numerous episodes of aqueous activity [184], with wet followed by dry spells and with water levels "gradually evaporating" [183]. As noted, sedimentary structures similar to stromatolites, dated to 3.7 billion years in age and which was fashioned in and exposed to a receding volume of water, have also been reported [34].

These findings—which are by no means conclusive—indicate that life may have appeared on Mars, between 3.7 bya and 4.2 bya, thus paralleling the emergence of Earthly life as indicated by the high concentrations of carbon 12 [185], the presence of graphite [186, 187] and carbon-isotopes and organic carbon discovered in apatite and quartz-pyroxene, and carbon-related evidence interpreted as the residue of photosynthesis, oxygen secretion, and biological activity dated to 3.8 bya to 4.2 bya [188–192]. Additional probable isotopic biosignatures have been identified in sulfur [188], nitrogen [193], and iron formations [194, 195], all dated to at least 3.8 bya.

Evidence indicative of fossilized fungi [196] and eukaryotic algae [197] have also been observed in sediments dated 3.8 bya—though not all investigators accept this evidence. In addition, remnants of ancient stromatolites that were fashioned in shallow water have been found in metacarbonate rocks aged 3.7 bya [33]. On Earth, the first stromatolites, therefore, may have been fashioned beginning around 3.7 bya [32, 33] most likely by algae (cyanobacteria)—though not all investigators agree with these dates.

11. The Interplanetary Transfer of Life

As reviewed in this report, there is evidence that life took root on a watery Earth and, possibly, on a warm watery Mars, early in the history of both planets, and these life forms may have been building stromatolites beginning 3.7 bya. The evidence suggestive of parallels in the origins of life on both planets supports the hypothesis that life on Earth and Mars may have originated from outside this solar system [198–200], and that these planets may have been colonized when first forming as protoplanets [113]. These scenarios would account for why there are chemical fossils on both planets suggesting that even as the earliest rocks were solidifying during the heavy bombardment, 4.2 bya, there was already evidence of life ([113]. It is also equally likely that life was delivered via meteors, asteroids, comets, and oceans of frozen water, during the heavy bombardment phase between 3.8 bya and 4.2 bya [201, 202], and/or that life-infested rocks, boulders, and mountains of soil were repeatedly ejected and transferred between Earth and Mars via meteor strikes

[192, 203–207] and powerful solar winds blowing upper atmospheric spores into the space [201, 208]—conditions under which algae, fungi, lichens, spores, and other microbes can survive [209–212].

Therefore, Mars and Earth may have been repeatedly seeded with life from outside this solar system and/or repeatedly exchanged life early in the history of both planets. This would account for evidence that life may have appeared simultaneously on Mars and Earth 4.2 bya, why stromatolites may have been constructed on both worlds 3.7 bya, and why specimens similar to algae, fungi, and lichens may be common to both planets.

12. Conclusions

Mars may have been a wet, habitable planet billions of years ago. In the last century, a number of scientists hypothesized that stromatolite-constructing cyanobacteria may have colonized Mars and urged that a search for these sedimentary structures should be undertaken. Subsequently, twenty-five investigators have published evidence of microstructures and macrostructures, photographed on Mars, which resemble stromatolites fashioned on Earth and in Lake Thetis in particular. If these Martian specimens are biological in origin is not known with absolute certainty as not all terrestrial stromatolites and thrombolites are biological [151, 152, 213, 214]. Therefore, the evidence reviewed here does not prove but supports the hypothesis that ancient Mars had oceans and lakes and was habitable and inhabited by organisms, which may have constructed stromatolites.

Data Availability

The data used to support this study are included within this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors have either contributed directly to the research reviewed and/or assisted in the analysis, writing, editing, and/in searching for and referencing the works cited.

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