Paleoecological Constraints on the Possible Nature of Life on Mars

Glenn Simonelli
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ABSTRACT: Recent Mars missions have provided extensive evidence that Mars once had pools of liquid water at its surface, and topographical data suggest that the northern hemisphere was once covered by a saltwater ocean. Conditions in this ocean may have been similar to conditions in early Earth oceans, leading to speculation that life might also have evolved on Mars. The length of time that Mars had continuously standing pools of liquid water on its surface could have had a profound influence on the nature and degree of evolution of life on the planet. Evidence suggests that this time may have been as little as 150 million years, raising the possibility that life on Mars may be very similar to some of the earliest life forms on Earth. Consideration of the nature of early Earth life forms and the possible role of horizontal gene transfer in driving the evolution of those forms raises the possibility that life on Mars may still be in a "pre-Darwinian" stage and not yet differentiable into separate Earth-like domains.

INTRODUCTION

Mars has long been an object of interest to astronomers and laypeople alike. It has been the object of numerous exploration missions, including four successful Mariner probes (1969-1972) and two Viking landers (1974). Currently NASA is mapping the planet with the Mars Orbital Laser Altimeter (MOLA), conducting high-resolution photography with the Mars Orbital Camera (MOC) and exploring the planet's surface with Spirit and Opportunity, the two Mars Rovers.

One of the reasons for this prolonged interest in Mars is the conjecture that Mars may have supported life in its past, or may be supporting it today. Although conclusive proof of bioactivity on Mars remains elusive, evidence is accumulating that raises the possibility. An assumption common among those actively investigating the possibility of exobiology—that is, life outside of Earth—is that one of the key elements for supporting Earth-like life is the presence of liquid water (McKay, *et al*, 1992; Jakosky, 1998). Confirmation of liquid water on Mars is one of the primary goals of the Mars Rovers expedition. This paper will examine some of the research addressing the possibility of liquid water on Mars and will discuss implications for life on Mars in view of this research.

WATER ON MARS

The Noachian Era

The geological history of Mars is divided into three major eras: the Noachian (4.6-3.7 bya), the Hesperian (3.7-1.0 bya) and the Amazonian (1.0 bya to present). The Noachian era corresponds to the Hadean era of Earth. During this time the solar system was still relatively young, and the inner planets were subject to frequent pummeling from asteroids and comets left over from accretion. It was during this period that Mars experienced the bulk of the cratering still visible on its surface (Jakosky & Phillips, 2001). The cessation of heavy cratering at the end of the Noachian era is fortuitous, because it allows scientists to date different areas of the Martian surface based on the amount of cratering visible today.

Early Martian Environment

It is reasonable to assume that comets impacting Mars brought combinations of volatiles similar to those brought to Earth, perhaps in higher abundances, (although many have subsequently been lost to space, [Squyers & Kasting, 1994]). Therefore, we can gain some idea of what the earliest environment of Mars may have been like based on what we know about Earth's early history.

<u>An Early Ocean.</u> Recent evidence acquired by the Mars Rovers has made the presence of large standing pools of salt water a near certainty (JPL press release, March 23, 2004). It is therefore reasonable to speculate about the role of surface water in shaping the early Martian environment. It is now widely accepted that Mars was much warmer and wetter during its earliest history (Jakosky, 1998). Because of the very thin atmosphere of Mars, surface erosion rates are very low, and geological features tend to exhibit very strong preservation (McKay, *et al*, 1992). The oldest craters and other geological features show rates of erosion several orders of magnitude higher than features formed later (Squyres & Kasting, 1994; Jakosky, 1998). This suggests that liquid water flowed over much of the Martian surface during this time. Surface features of Mars show evidence of runoff valleys formed during the Noachian era (Head, *et al*, 1999; Hynek & Phillips, 2003). Many of these runoff valleys are notable because of their distinctive V-shaped troughs—suggestive of precipitation run-off—whereas if the valleys were

formed tectonically or glacially U-shaped troughs would be expected (Fanale, *et al*, 1992). Recently, extensive drainage systems have been identified from images taken by the Mars Orbital Camera (MOC), suggesting that Mars once experienced significant precipitation (Hynek & Phillips, 2003).

The southern hemisphere of Mars exhibits extensive cratering, but the northern hemisphere shows very few craters. This difference is significant. There is no reason to assume that the northern hemisphere experienced fewer impacts, so any difference in the number of visible craters must be due to differences in preservation. Clearly, the northern hemisphere was subjected to erosional influences not present in the southern hemisphere (Jakosky & Phillips, 2001).

Recent MOLA data has confirmed that the northern hemisphere of Mars is ~5 km lower in elevation than the southern hemisphere (Zuber, *et al*, 2000). Furthermore, MOC image analysis reveals that many outflow channels and drainage systems flow into these northern lowlands (Head, *et al*, 1999). Precipitation on Mars would have eventually drained into the northern lowlands, suggesting that early in its history Mars's northern hemisphere was covered by a vast saltwater ocean (McKay, *et al*, 1992; Jakosky, 1998). An analysis of MOC data has led to the identification of likely shorelines (Clifford & Parker, 2001, see Fig. 1), suggesting that water from outflow channels drained into the large northern ocean (Head, *et al*, 1999). Recent analysis of MOLA data reveals that the crust of the Northern hemisphere is much thinner than the southern. There is speculation that the northern hemisphere may have experienced plate tectonics during the Noachian era (Zuber, *et al*, 2000). Sub-marine tectonic activity likely would have created hydrothermal vents, injecting large amounts of sulfur into the anoxic waters. This suggests the possibility of localized environments similar to those suspected by many of initiating or harboring the earliest life on Earth. (Nisbit, 2000; Sankaran, 2000).

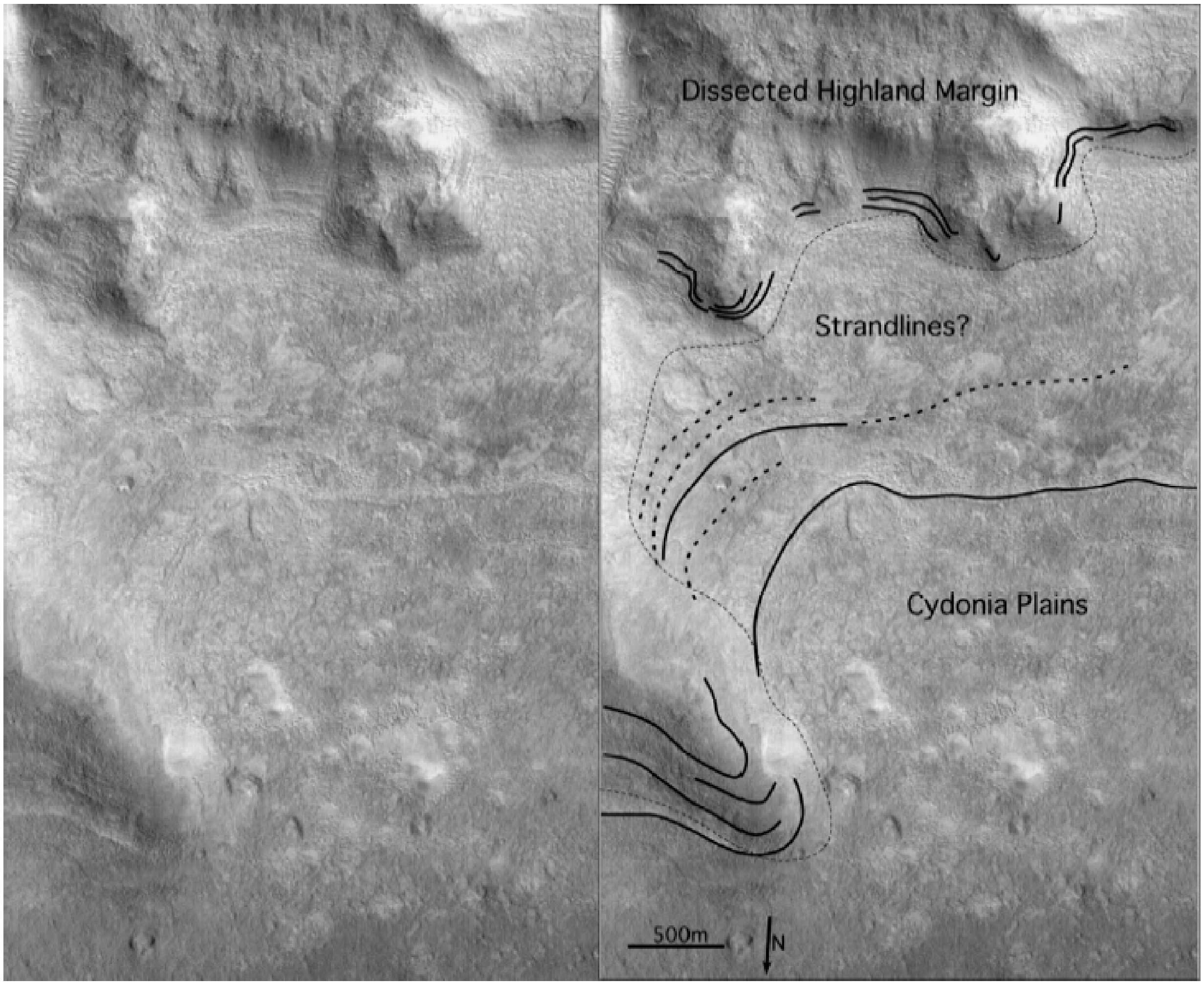

Figure 1: An image from the northern hemisphere of Mars (36.45º N, 9.14 W º) taken by the MOC showing parallel ridges identified as shorelines by Clifford & Parker (2001). The image on the right shows the different shorelines draw in by the authors. (MOC image MO7-04326).

Earth analogues. The pursuit of the discovery of life on Mars eventually leads one back to Earth. Since Earth is the only planet that we know for certain to be supporting life, our knowledge of the processes and constraints of life is restricted to what we can discover on our own planet. It is necessary to extrapolate this knowledge to known conditions on Mars to develop assumptions about the Martian environment. To this end, much effort is being directed to identifying places on Earth with environments similar to areas of Mars, with the goal being to predict the nature of life forms capable of surviving on Mars under similar conditions. Farr (2004) reports recent or current geological investigations into evaporates and dry lake beds in the Mojave Desert/Death Valley region, Arizona, the Colorado Plateau, the Channeled Scablands, central Australia, the Sahara Desert, Tunisia and the Dead Sea. Permafrost and other sub-zero temperature phenomena are being examined in Antarctica, the High Arctic, Alaska and Canada. The role of volcanism and impact craters is also under investigation at various locations. All of the investigations listed by Farr aspire to add new information to the discussion of what factors impact the possibility of life on Mars. For example, Fernández-Remolar, *et al*, (2004) have proposed that the chemistry of the Tinto River basin in Spain provides a good analogue to the chemistry of the large body of water thought to once exist in the Terra Meridiani on Mars. Douglas (2004) has identified structural and chemical biosignatures in evaporate deposits from Death Valley, California, as possible analogues to exobiological signatures.

The Ross Desert and the McMurdo Dry Valley in Antarctica are frequently cited as Mars-like environments, and extremophilic life discovered in this cold, dry environment is frequently proposed as an Earth analogue to possible Martian life. Vestal (1988) has studied cryptoendolithic microbes (microbes living inside of rock) in the Linnaeus Terrace of the Ross Desert, and is looking at the use of phospholipids as a possible measure of biomass.

Although much of the speculation about hypothetical Martian biology centers on likely Archaean or bacterial analogues, some recent research considers the potential for Eukarya on Mars. Vestal focused his research on lichens. Onofri, *et al*, (2004) propose that Antarctic cryptoendolithic microfungi should also be considered likely candidates for analogues of Martian life. They point to the ability of many Antarctic microfungi to survive the extreme cold and desiccating conditions of the planet. Also, although the extremely thin atmosphere of Mars allows normally lethal levels of UV radiation to reach its surface, the documented ability of the Antarctic microfungi to withstand exposure to elevated levels of UV radiation and radioactivity increase their survivability potential on Mars. (For reasons that will be discussed later, this argument is made more credible if one accepts the proposal of Martin, *et al,* 2003, that fungi were one of the earliest forms of Eukarya.) However, the discovery that the bacterium *Deinococcus radiodurans* could withstand ionizing radiation 1,500 times the level lethal to all other known organisms (Levin-Zaidman, *et al*, 2003) has strengthened the argument for bacterial life on Mars.

Currently, speculation about the nature of hypothetical life on Mars is going in many different directions, and many different Earth analogues have been proposed as models for possible Martian life. A closer examination of the fate of standing water on the Martian surface may help to narrow down the list of different possible models.

<u>Fate of the ocean</u>. Today there is no liquid water on the Martian surface; it is usually too cold for water to exist as a liquid, and the atmospheric pressure is so low that any liquid water present would rapidly boil away into the atmosphere (Jakosky, 1998). Therefore, the recently discovered evidence of liquid water flowing on the Martian surface in the past suggests two things: the surface temperature of the planet was much warmer (above the melting point of saltwater), and the atmospheric pressure was much greater (to keep liquid water from boiling

into vapor). There is much evidence to suggest that both these conditions were met, as well as evidence that suggests these conditions ended quickly at the end of the Noachian era.

Although the ocean is no longer present, the paucity of impact craters on the northern hemisphere suggests that the ocean lasted at least until the end of the Period of Heavy Bombardment (PHB). Although it is possible that Mars accreted in significantly less time than Earth or Venus (Lunine, *et al*, 2003), it was still subjected to continual comet and asteroid impacts during its early years. Lunine, *et al*, propose that it was through transport by comets that Mars acquired the bulk of its surface water. Therefore, it is reasonable to assume that Mars emerged from the PHB with its northern ocean intact. There is currently much speculation about how much longer the ocean may have remained on the surface, but recent models suggest that liquid water may not have lasted on the surface for long after the end of the Noachian era (Clifford & Parker, 2001).

In order for water to exist in a continuous liquid state at the surface, the average surface temperature (AST) must have been much higher than it is today. Currently Mars has an AST of ~210º K. To keep water as a liquid at its surface, Mars would need an AST of at least 273º K. (Depending on the salinity of the water, this number could be slightly lower.) Our current model of stellar evolution suggests that the Sun was 30% less bright during the Noachian era than it is today (McKay, *et al*, 1992; Squyres & Kasting, 1994), meaning that Mars received 30% less warming from the Sun than it does today. Absent any greenhouse warming, this reduced solar energy would have reduced the AST of Mars to ~198º K (author's calculation; see Appendix). Something must have helped maintain the planet's AST at least 75º K higher than would be expected based on the amount of solar radiation received.

Greenhouse warming is often proposed as a possible mechanism for keeping the AST at a level necessary to melt water. Jakosky & Phillips (2001) point out that Mars atmosphere is enriched in heavier isotopes of Argon, Carbon, Nitrogen and Oxygen. Since lighter isotopes tend to rise to the upper regions of the atmosphere, this suggests that the Martian atmosphere was much denser in the past but has since been stripped by interaction with solar wind. Additionally, some of the liquid water on the surface would have evaporated into the atmosphere (Lunine, *et al*, 2003) increasing the amount of greenhouse gasses in the atmosphere and warming the planet even more. But greenhouse warming does not appear to account for enough extra warming to raise the surface temperature above the melting point of water ice over most of the planet. The amount of CO_2 currently detectable on the planet, and assumed to be sequestered in the lithosphere, does not appear to be nearly enough to increase the AST by 75º K (Squyers & Kasting 2004; Jakosky & Phillips, 2004). Squyers & Kasting show that under an earlier, cooler Sun, clouds of CO_2 ice would have filled the Martian atmosphere, increasing its albedo—the measure of the portion of energy received from the Sun that is reflected back into space—and further reducing its surface temperature. Furthermore, impacts during the period of heavy bombardment would have driven much of the early Martian atmosphere off into space, making an adequate greenhouse effect even less likely. (Mars has a much lower escape velocity than Earth or Venus, so gases can be driven off into space more readily.)

However, those same impacts may have contributed to the warming of the planet. The process of accretion significantly heated the planet, and the added heat from bollide impacts, as significant percentages of the kinetic energy of the moving bollides was transferred as heat into the lithosphere, contributed to and helped maintain the residual accretion-generated heat for most of the Noachian era, creating a much higher planetary temperature gradient during this time period. The result was that much more of the planet's interior heat was transferred to the surface. (Fig. 2). Calculations by Zuber, *et* al, (2000) show that the northern hemisphere experienced particularly high heat flow in the early Martian history. The increased interior heat flux would have melted any ground ice and brought much of it to the surface.

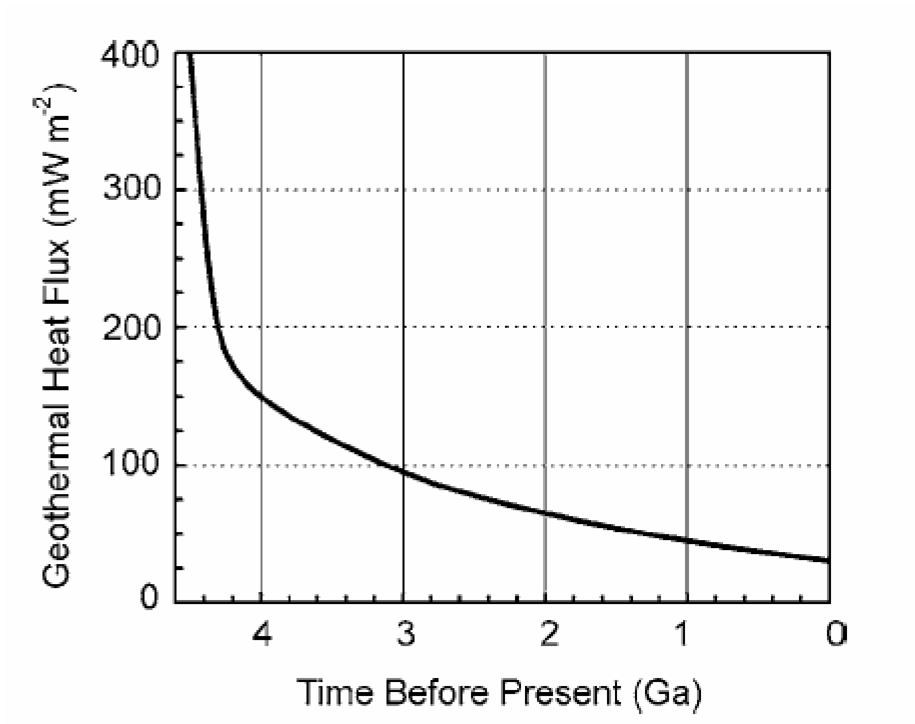

Figure 2. Geothermal heat flux over time. Geothermal heat was several times present levels at the end of the Noachian era, 3.8 bya (Clifford and Parker, 2001, after Stevenson *et al*, 1983).

However, increased heat flow alone is not capable of keeping liquid water at the surface. Without an increase in atmospheric pressure, liquid water at the surface would have boiled away into the atmosphere. So a much denser early atmosphere is still required to explain the presence of a large northern ocean.

Knowing these two requirements—increased interior heat flow to the surface and a thicker, denser atmosphere—allows us to speculate how long liquid water could remain on the surface after the end of the Noachian era. As can be seen in Figure 2, geothermal heat flux drops very rapidly during the Noachian era. Because of its relatively large surface area compared to its total volume, Mars radiates heat rapidly. Absent the additional regular input of kinetic energy from bollide impacts, Mars cooled quickly and was unlikely to be able to maintain liquid water at its surface much beyond the Noachian era.

In its early history the Martian atmosphere would have been protected from stripping by solar wind by its magnetosphere. However, Jakosky & Phillips (2001) present evidence that the protective magnetic field had disappeared early in its history, possibly as early as the end of the Noachian era. This would have left the atmosphere vulnerable to rapid depletion by the solar wind, and would have required a continual input of CO_2 into the atmosphere to maintain the pressure needed to keep water as a liquid at the surface. The Tharsis Rise is an area of high elevation on Mars notable for the presence of several volcanoes. The formation of this region was likely accompanied by large amounts of CO_2, water vapor and possibly CH_4 being pumped into the atmosphere (Squyers & Kasting 2004; Jakosky & Phillips, 2004), and possibly raising the AST of the planet enough to compensate for the declining interior heat flux. As long as the Tharsis Rise was actively forming, conditions necessary to maintain the northern ocean may have been possible in spite of a declining heat flux.

Recent evidence suggests that the Tharsis Rise formed during the Noachian era and that its formation marked the end of regular massive tectonic activity (Zuber, *et al*, 2000; Jakosky & Phillips, 2001). The cessation of significant tectonic activity around this time ended the massive infusion of CO_2, water vapor and CH_4 into the atmosphere. (There is no reason to assume that all tectonic activity ceased at this time, but any subsequent contribution of CO_2 or CH_4 to the atmosphere was likely several orders of magnitude less than during the Noachian.) Without additional regular contributions of CO_2, the atmosphere thinned through sequestration of CO_2 into the lithosphere and escape of atmospheric gases into space. Subsequently, the atmospheric pressure dropped to the point that any remaining liquid water boiled into the atmosphere. It is possible that, if surface temperatures drop due to declining heat flux before the depletion of the atmosphere, the northern lowlands could have become ice-covered, preserving the liquid state of the saltwater for somewhat longer into the Hesperian (McKay, *et* al, 1992; Clifford & Parker, 2001). However, continuing decline of the heat flux would have led to the northern ocean eventually freezing solid and finally sublimating into the thinning atmosphere, leaving the surface dry and barren. Although the length of time that liquid water flowed continually on the surface is not certain, Squyres & Kasting (1994) and Jakosky (2001) present very compelling arguments that Mars' "wet" period could not have lasted much beyond 3.7 bya.

It should be noted, however, that the end of the Noachian era does not mark the end of water on Mars. Clifford & Parker (2001) present a detailed analysis of water locked up as ground-ice near the surface and remaining as a liquid deeper underground. It is possible that any life on early Mars could have survived by moving underground. Calculations by Weiss, *et al*, (2000) show that there is sufficient energy in the form of photochemically produced H_2 and CO available through diffusion below the surface to sustain life. Clifford & Parker suggest several scenarios where groundwater is temporarily able flow out from underground at higher elevations into lower depressions during the Hesperian era due to pressure build-up caused by the expanding cryosphere. Cabrol, *et al*, (2001), examine MOC images and identify gullies representing likely outflow channels in craters. According to Cabrol, *et al*, subsurface life could occasionally be brought to the surface via meteor impacts, as kinetic energy from the bollide is transformed into heat energy, melting the surrounding cryosphere. Melted ground ice would then flow into nearby crater basins (Fig. 3), forming temporary crater lakes. Yet these temporary outflows are significantly different than the large, stable northern ocean discussed previously. Liquid water spilling through outflow channels would not remain on the surface for long; most of it would rapidly boil away into the atmosphere. Melted groundwater would quickly re-freeze. Although these pools would present radical climatic change to any organisms trapped within ground-ice, their ephemeral nature would create an evolutionary dead end. (They might, however, prove to be excellent sources of biomarkers [Cabrol, *et* al, 2001].)

Thus, it is reasonable to assume that the end of the Noachian era also marked the end of continuously standing liquid water on the Martian surface. After that time, water could only remain as a liquid deep underground, where it could be kept warm by the thermal gradient of the planet (Clifford & Parker, 2001).

SPECULATING ABOUT LIFE ON EARLY MARS

The end of the Noachian er of Mars approximately corresponds to the transition from the Hadean to the Archaean era on Earth. This time period may have marked the beginning of life on Earth.

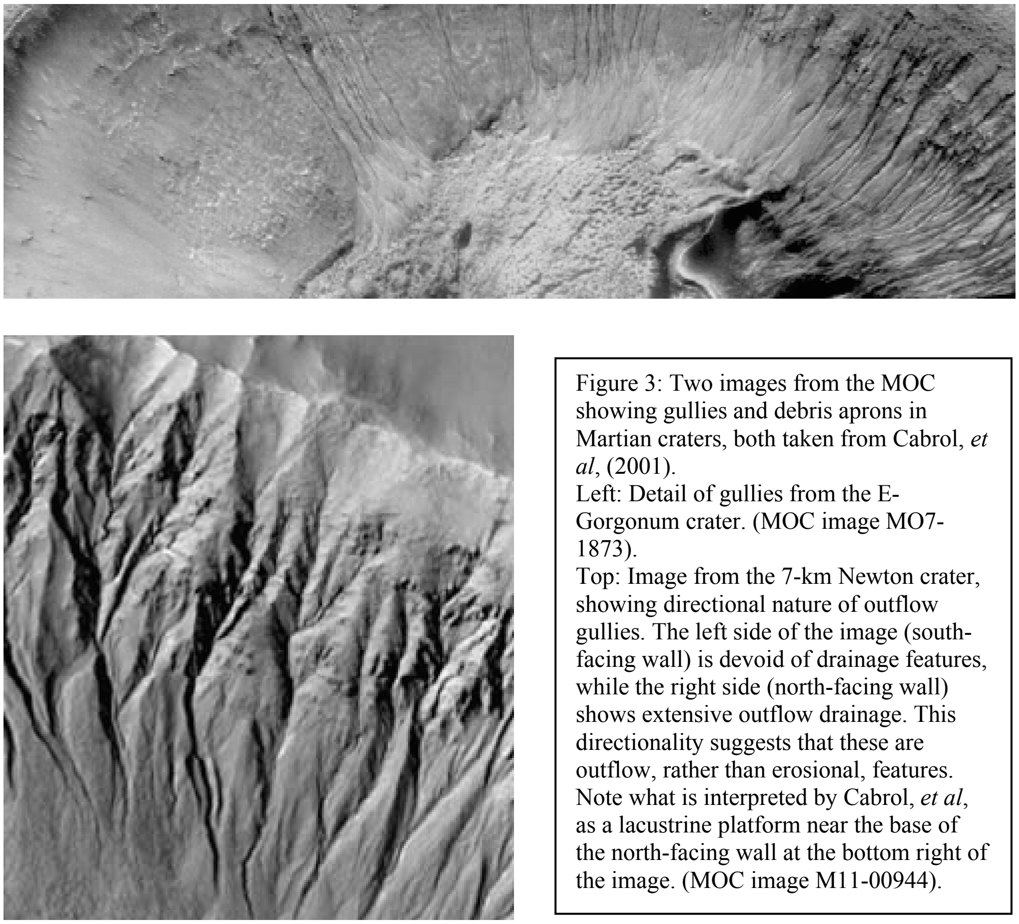

Figure 3: Two images from the MOC showing gullies and debris aprons in Martian craters, both taken from Cabrol, *et al*, (2001).
Left: Detail of gullies from the E-Gorgonum crater. (MOC image MO7-1873).
Top: Image from the 7-km Newton crater, showing directional nature of outflow gullies. The left side of the image (south-facing wall) is devoid of drainage features, while the right side (north-facing wall) shows extensive outflow drainage. This directionality suggests that these are outflow, rather than erosional, features. Note what is interpreted by Cabrol, *et al*, as a lacustrine platform near the base of the north-facing wall at the bottom right of the image. (MOC image M11-00944).

It is assumed that the PHB of Earth ended around 3.8 bya, and there is every reason to believe that this period ended at about the same time on Mars (Jakosky & Phillips, 2001). Prior to this time, any life beginning to emerge on Mars was likely wiped out by the sterilizing effects of the heat generated by meteor impacts (Ward & Brownlee, 2000). Therefore, any Earth-like life appearing on Mars that might still be recorded in the fossil record (or possibly still surviving underground today) had to have arisen between the end of the heavy bombardment and the end of liquid water on the surface (McKay, *et al*, 1992).

Conditions Driving Evolution

Life on Earth tends to show the greatest complexity at or near the surface. While the reason for this is not certain, it is worth noting that the surface of the Earth is subject to climatic change. Since climate change is much more rapid than geologic change, an argument could be made that environmental change is one of the driving forces for evolution and the push toward biological complexity. Organisms sheltered from environmental change may experience less pressure to develop new adaptations, although this is just conjecture.

If there is cryptoendolithic life on Mars, what might it look like? If the conditions necessary to allow water to exist as a liquid on the Martian surface ended around 3.7 bya, then that presents a very small window for life to have survived at the surface of the planet. If we assume that life on Mars arrived from the same source at about the same time as on Earth—a reasonable assumption, but by no means a certainty—we will assume that possible evolutionary conditions on Mars paralleled those on Earth for approximately 150-200 million years, after which time drastic environmental changes created profound evolutionary stresses that drove any life on Mars deep underground, possibly following the descending hydrosphere/cryosphere boundary, into much more shielded, stable and evolutionarily stagnant environments. Whereas on Earth evolution continued to spiral outward along a pace dictated by the pace of climate change, on Mars it was plunged into a 3.7 Ga deep freeze, change restricted to the slow, methodical rate of geologic change.

Conditions on Mars during the later Noachian era may have been favorable to the support of life. A thermally heated saltwater ocean could have provided all the conditions necessary for the development and/or support of life (McKay, *et al*, 1992).

If evolution of the life on Mars proceeded at a rate similar to that on Earth's surface for only 150 – 200 million years, what might that life be like today? We might gain some idea by looking at some of the earliest life forms on Earth. Unfortunately, we have no record of any life that might have appeared before the end of the Period of Heavy Bombardment (PHB). We do, however, have hints that life began to take hold on Earth shortly after the end of the PHB.

Earliest life on Earth. On Earth there is evidence that life appeared as early as 3.85 bya (Mojzsis, *et al*, 1996). The earliest hints come from rocks known to be more that 3.8 Ga old (Nisbit, 2000). Although there are no known fossils from this time, there is much isotopic evidence to support biogenic activity (Mojzsis, *et al*, 1996; Rosing, 1999; Rosing & Frei, 2003). As organisms use carbon to build biomass, they tend to take up ^{12}C more easily than ^{13}C, creating a reduction in the typical $^{12}C/^{13}C$ ratio. This depletion in the ratio is generally taken as a marker of biological activity. Mojzsis, *et al*, have found this signature in banded-iron formations in West Greenland. This depletion was also reported by Rosing in other rocks from the same area. He presents evidence of reduced $^{12}C/^{13}C$ ratios to suggest that photoautotrophic planktonic organisms may have been abundant before 3.7 Ga.

The earliest fossil evidence of life comes from the Warrawoona Group in Australia. Schopf & Packer (1987) reported the discovery of colonies of filamentous microorganisms with cells types similar to modern cyanobacteria in rocks dated to 3.3-3.5 Ga old. This suggests that oxygen-producing photosynthesis, a complex metabolic process, was occurring within a few hundred million years of the development of the earliest life forms. This assertion has profound implications, for it suggests that life moved rapidly toward complexity after its initial appearance. Recently, however, Schopf & Packer's conclusions have been called into question.

Brasier, *et al*, (2002; 2004) have proposed non-biological processes as the cause of the so-called microfossils reported by Schopf & Packer. Brasier, *et al*, go on to question the evidence supporting the existence of any life on Earth prior to ~2.5 bya. They suggest that the carbon ratio depletion could be caused by tectonic activity, providing a description of abiotic processes possibly creating it. They further assert that, until all possible abiotic explanations for the carbon isotope ratio depletion are ruled out, arguments for biotic origins are invalid.

If the argument put forth by Brasier, *et al*, is correct, it would severely reduce the likelihood of life on Mars. The rapidity with which life arose on Earth is often used as key supporting evidence for the argument that life may be abundant in the universe, (Ward & Brownlee, 2000), and, by inference, on Mars. If, however, life took over 1 billion years to develop on Earth, then that would push its emergence well beyond the range of the continual presence of liquid water on the Martian surface. It could, in fact, suggest that the search for life on Mars is doomed to be fruitless.

However, the argument against early biogenecity by Brasier, *et al*, raises a standard for its rejection that is impossible to achieve. They propose that:

> Very ancient/alien microfossil-like structures (or stromatolites or geo-chemical and isotopic signals older than c. 3.0 Ga) should not be accepted as being of biological origin until possibilities of the non-biological origin have been tested and can be falsified (2004, p.259).

This suggested methodology, disproving a null hypothesis, may not be an appropriate test for biogenecity, because it requires the logical impossibility of proving a negative. Additionally, several authors have recently come forward to argue the case for the early emergence of life on

Earth. Kazmierczak & Kremer (2002) suggest that the filamentous arrangement of the microfossils was caused by thermal alteration, suggesting that, although the complex stromatolitic arrangement of the microfossils may have been caused by abiotic processes, the microfossils themselves are of biotic origin. Ueno, *et al*, (2004) have examined various scenarios surrounding the formation of hydrothermal silica dikes in Western Australia. They conclude that, although abiogenecity can not be completely ruled out, a biological origin of the carbon isotope ratio depletion is much more likely. Furthermore, Furnes, *et al*, (2004) report the presence of micrometer-scale tubes in c. 3.5 Ga. pillow lava. These tubes contain organic carbon at their bases with a distinctive isotopically light carbon ratio. They conclude that these tubes are evidence of microbial activity that occurred shortly after the eruptions that generated the lava.

Other researchers are offering evidence of fossils much older that the 2.5 Ga date accepted as the earliest conclusive date given by Brasier. Rasmussen reports the presence of filamentous microfossils in 3.2 Ga. sulfide deposits. Altermann & Kazmierczak (2003) reviewed many claims of Archaean era fossils and concluded that fossils from 3.46 Ga Australian chert and the 3.49 Ga Dresser Formation, also in Australia, were authentic, although they question whether Archaean stromatolites should be considered fossils in the strictest sense.

Although the null hypothesis of Brasier, *et al,* may not be conclusively disproved, a preponderance of evidence suggests biological activity was well under way by 3.5 bya. Still, the existence of complex colonies of photosynthesizing cyanobacteria may be open to question. If the Warrawoona stromatolites (Schopf & Packer, 1987) prove to be thermally altered microfossils of much more primitive life forms, then that could extend the time span that life existed on the planet in a simpler form, challenging the notion that life on Earth initially evolved and achieved complexity very rapidly. That would paint a very different picture of what life on Earth was like during the first 350 million years of its existence.

Horizontal gene transfer. Recently, many researchers have been considering the role of horizontal gene transfer (HGT, also called lateral gene transfer) in the development of early life on Earth. Brown (2003) defines HGT as "the exchange of genes between species from different domains of life" (p.122). Martin, *et al*, (2003) argue that early life on Earth was dominated by HGT, citing the appearance of much prokaryotic genetic information in modern eukaryotes today as supporting evidence. Woese (2002) suggests that the early evolution of life was paralleled by cellular evolution. Both Brown and Martin, *et al*, suggest that HGT played such a significant role in the early development of life that the current phylogenetic tree of life may need significant revision to incorporate its effects. Taken together, these authors paint a vastly different picture of cellular evolution than that suggested by traditional Darwinian evolution. In fact, traditional Darwinian evolution was possibly not a factor in the early history of life on Earth.

Unlike today, bacterial, archaeal and eukaryal domains were not distinguishable among the earliest life forms. Woese argues that early cells were much more primitive that those of today, and he proposes that they could easily assimilate genetic material from other nearby cells. He argues that, because of easy, rapid genetic and subsequent morphological changes, early cells were indistinguishable from each other and that genetic differences could be identified only between communities of cells. As these communities became more widely physically and, therefore, genetically separated, the ability of a cell to accommodate genetic material from other communities diminished. Eventually cells became so sophisticated and/or specialized that genetic material could be exchanged only rarely, if at all. Eventually, the primary method of passing on genetic information becomes vertical, through descendant cells. Woese defines this point as the “Darwinian Threshold.” It is not until a community of cells surpasses its Darwinian Threshold that those cells can be considered part of an identifiable domain. Furthermore, there is no reason to assume that the three currently accepted domains of life crossed their Darwinian Thresholds at the same time. Brown (2003) argues that Eukarya developed long after Archaea had become differentiated from bacteria. Woese suggests that Bacteria may have been the first domain to cross the Darwinian Threshold, implying that there may have been a long period when life on Earth was either bacterial or undeterminable.

This period of un- and limited-differentiability may be reflected in the lack of concrete fossil evidence from the first ~350 million years of life on Earth. If early cells were much less sophisticated and distinct, the nebulous, primitive nature of these early cells might have prevented them from being recognizably preserved as fossils. It is therefore possible that life on Mars, if it originated and developed in a way similar to Earth’s, might have required a similarly long period of pre-Darwinian development before it achieved a level of sophistication necessary to differentiate into distinct domains. If, as currently seems likely, life on Mars had only a 150-200 million year span to evolve at a climate-driven rate before being driven underground into evolutionary “slow motion,” it is possible that some, or even all, of Martian life is still in a pre-Darwinian Threshold stage. Life on Mars might prove to be a “living museum,” providing a glimpse of some of the earliest life processes on Earth. It is further possible that life on Mars might still be in an undifferentiable form, or that, reflecting Woese’s ideas, that Bacteria may be differentiable from other, undifferentiable forms, or that, reflecting

Brown's ideas, that life might be separable into Bacterial or Archaeal domains without any Eukaryal representatives yet evolved.

CONCLUSION

Recent evidence discovered by the Mars Rover vehicles creates a very strong case for the existence of liquid water on the Martian surface over an extended time, beginning during the Noachian era. Geological evidence suggests that the northern hemisphere of the planet was covered by an anoxic, sulphitic ocean, which appears similar to the oceans of Earth during its early history. Atmospheric and heat dissipation models suggest that the conditions needed to maintain this ocean may have ended by 3.7 bya.

If the origination and evolution of life on Mars paralleled that of Earth's, then conditions for rapid, climate-driven evolution could have lasted for as little as 150 million years, before being driven progressively deeper underground. It is therefore possible that any life on Mars today may be restricted to a very early form of development, perhaps with representatives still in a pre-Darwinian stage of evolution.

Discovery of life on Mars could provide several key insights into life on Earth. It may illuminate what early life on Earth was like, providing insights into the nature of HGT and its impact on early evolution. It could reveal whether life did begin in an undifferentiable phase and, if so, whether the Bacterial-Archaeal-Eukaryal division is inevitable or unique to life on Earth.

APPENDIX

Formula used to calculate average surface temperature

Calculating the average surface temperature of Mars without any greenhouse warming is relatively straightforward. The amount of energy arriving at the planet is calculated first and then reduced by the amount of energy reflected back into space due to the bond albedo. Finally, because Mars is not a perfect black body radiator, a slight adjustment is made for emissivity.

Mass. The equation for the amount of energy emitted by a star is: $L = 3.846 \times 10^{33} \times M^3 e/s$, where *L* is the luminosity in ergs per second and *M* is the mass of the star in solar masses. (One solar mass equals 2.0×10^{33} grams.) The Sun has a solar mass of 1. For this calculation the luminosity must be reduced by 30% to compensate for the reduced energy output of the early sun. Since *L* is proportional to the cube of *M*, *M* is set to .89

Distance. Distance is entered in Astronomical Units (AU). $D = AU \times 1.496 \times 10^{13} cm$. Mars' average orbital distance is 1.52 AU.

Bond Albedo. Bond albedo (A) for Mars is approximately 25%, entered as a decimal.

Effective Temperature. Effective temperature can be calculated using the general equation $Rate_{IN} = Rate_{OUT}$. $Rate_{IN}$ is derived from the formula $R_{IN} = (\frac{L}{4\pi D^2})\pi R^2 (1 - A)$.

$(\frac{L}{4\pi D^2})$ is "flux" in erg/cm^2/sec, πR^2 is the cross section of the planet, and (1-A) is the fraction of starlight absorbed. $Rate_{OUT}$ is calculated as $(4\pi R^2)(\sigma T^4)$, where $(4\pi R^2)$ is the area of the planet and (σT^4) is the formula for hot "black" body radiation. σ is the Stefan-Boltzman constant, equal to $5.6703 \times 10^{-5} watts/cm^2/T^4$, and *T* is temperature in degrees Kelvin.

Canceling out R^2 and solving for T yields the following formula for effective temperature:

$$T_{eff} = \left[\frac{(1-A)\times L}{16\pi\sigma}\right]^{1/4} \times \frac{1}{\sqrt{D}} .$$

Emissivity. Because Mars is not a perfect black body radiator we needed to add a slight corrective factor to T_{eff} . This factor is $\varepsilon = 0.9$ and it is multiplied to T_{eff} .

Surface Temperature. Surface temperature can now be calculated with the formula: $T_{surface\,^\circ K} = \sqrt[4]{T_{eff}^4 \times 0.9}$. Finally, substituting for T_{eff}^4 yields:

$$T_{surface\,^\circ K} = \sqrt[4]{\sqrt[4]{\frac{(1-Alb)\times(3.846\times10^{33} \div M^3)_{e/s}}{16\pi\times5.6703\times10^{-5}_{watts/cm^2/^\circ K^4}}} \times \frac{1}{\sqrt{AU\times1.496\times10^{13}_{cm}}} \times 0.9} .$$

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