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Mars: A Reassessment of its Interest to Biology

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Of all the other planets in our solar system, Mars is certainly the one that has inspired the most speculation concerning extraterrestrial life. Looking through telescopes, observers had long noticed that Mars exhibits changes in its polar caps and alterations in its surface coloration that parallel seasonal changes on Earth. Seasons result from the axial obliquity, and the Martian obliquity (25°) is very close to that for the Earth (23.5°). Mars is the only planet in the night sky which exhibits such an Earth-like pattern of seasonal change. This similarity may have been the basis for the early speculation that Mars was the home to civilizations: ancient, warlike, wise, or on the eve of destruction—depending on the author's inclination.

The fascination with Mars and the possibility of life on Mars continued into the spacecraft era and was directly expressed in the Viking Missions. These highly successful missions had the search for life on Mars as one of their principal goals. To conduct the search two identical

landers set down on opposite sides of the Martian northern hemisphere.

In addition to the lander cameras, which would show the presence of any obvious macroscopic life-forms, and the GCMS (Gas Chromatograph/Mass Spectrometer) which searched for organics in the soil, the Viking landers contained three experiments specifically designed to search for indications of life on Mars: The Gas Exchange (GEX) experiment was designed to determine if Martian life could metabolize and exchange gaseous products in the presence of water vapor and in a nutrient solution. The Labeled Release (LR) experiment sought to detect life by the release of radioactively labeled carbon initially incorporated into organic compounds in a nutrient solution. The Pyrolytic Release (PR) experiment was based on the assumption that Martian life would have the capability to incorporate radioactively labeled carbon dioxide in the presence of sunlight (i.e., photosynthesis). In addition, the X-ray Fluorescence experiment analyzed the elemental composition of the loose material at the Viking lander sites. Unfortunately, from the biology perspective, the instrument could only detect elements with atomic number greater than that of Mg. Thus there was no direct measurement of O, N, C, or H in the soil material.

The Viking results indicated that the surface of Mars is a cold dry desert. The thin atmosphere (about 8 mb surface pressure) is composed of 95% CO_2 with 1.5% N_2 present. Water is also present in the atmosphere at about 0.03% and in the soils at the Viking lander sites with concentration of a few percent by mass. Phosphorus was not detected because its signal in the X-ray Fluorescence instrument was hidden by that of S and Si—both of which were present—but is nevertheless thought to be present. Thus all the biogenic elements (C, H, N, O, P, S) are present on the surface of Mars.

Perhaps the most surprising result of the Viking soil analysis was the virtual lack of organic carbon in the soil. The GCMS failed to detect organics in surface samples and from samples below the surface (maximum depth sampled was about 10 cm) at parts per billion levels. There are at least two mechanisms that could produce organics on Mars. One mechanism is the importation of organic material by the infall of meteorites, many of which are known to carry organic material. A second mechanism is the production of organic material by UV light incident on the surface, as demonstrated in the Viking Pyrolytic Release Experiment. Hence, the absence of organics suggests that a mechanism for destroying them is present. All that the GCMS did detect were traces of the cleaning fluids used in preparing the instrument before launch. The lack of organics in the Martian soil is certainly a persuasive argument against the presence of life at the Viking landing sites.

Yet, the Viking Biology instruments gave interesting results. In the GEX experiment, the soil released O_2 upon humidification in amounts ranging from 70-790 nmoles cm^{-3}. Heating of the sample to 145°C for 3.5 hours reduced the amount of O_2 released by about 50%. There was a slow evolution of CO_2 when nutrient was added to the soil. In the

LR experiment there was a rapid release of CO_2, followed by a prolonged slow release of CO_2, from radioactively labeled C in the nutrient solution. The effect was completely removed by heating to 160°C for 3 hours, partially destroyed at 40–60°C, and relatively stable for short periods at 18°C, but was lost after long-term storage at 18°C.

The chemical activity and lack of organics is likely caused by reactions with one or more oxidants in the Martian soil. The chemical composition of these oxidants is not certain. Based upon the GEX and LR results, there must be at least three oxidants on Mars. The GEX results imply the existence of a strong oxidant that is thermally stable and capable of breaking down water to release oxygen. A second strong oxidant must exist to explain the LR results. This oxidant differs from the GEX oxidant in that it is thermally labile. A third, weak, oxidant (γ-Fe_2O_3) is required to explain the slow oxidation of the nutrient in the GEX experiment and the release of CO_2.

Possible oxidants for the GEX oxidant include KO_2, ZnO_2, and CaO_2. These oxidants would need to be present at concentrations of about 2-25 ppm by mass to match the experimental results. A possible oxidant for the LR oxidant is H_2O_2, catalyzed in the surface by the soil minerals. H_2O_2 could be produced in the atmosphere from photochemical reactions at a rate of about 2×10^9 molecules cm^{-2} s^{-1} and could be the source of the oxidants in the LR experiment. The concentration of H_2O_2 required to explain the LR results is about 1 ppm by mass.

Alternative explanations for the Viking biology experiments include the suggestion that the chemical reactions were due to peroxonitrite or to intrinsically reactive clays or the production of radicals such as OH^- resulting from chemical weathering processes in the soil without any UV excitation. It has been suggested that the O_2 released in the GEX experiment could be due to physically trapped O_2 within micropores or the release of physically absorbed gases in the Martian soil, with no chemical reactions necessary to explain the results.

Thus, the Viking Missions returned a negative, but still equivocal, answer to the question of life on Mars. Extending the unfavorable results to the rest of the Martian surface may not be justified given our present state of knowledge of Mars. Furthermore, the two Viking sites were similar in that they were both covered by a mantle of windblown dust. Although this dust layer appears to be ubiquitous on Mars, localized spots may exist that have quite different conditions than the Viking lander sites. However, in at least two respects the prospects for life anywhere on Mars is diminished. First, if the oxidants that were thought to have been detected at the Viking lander sites are produced by photochemical reactions then they should be found everywhere on the planet with the concomitant destruction of organic material. Second, but more seriously, the amount of water anywhere on Mars is quite low and there is no indication that liquid water is found anywhere at any season. Without liquid water there is no prospect for the growth of life as we know it; for example, bacteria require water activities above 0.6 for metabolism.

While the spacecraft exploration of Mars has diminished hopes of finding extant life forms on its surface, it has also shown us that many years ago Mars was a very different place and enjoyed conditions that may have been conducive to the origin of life—life that may have long since become extinct.

From a biological perspective, the most important information returned from spacecraft exploration of Mars may be the geological evidence that liquid water was abundant on the Martian surface at some time in the past. The most compelling evidence for liquid water comes from the observation of riverine features. These include the outflow channels and valley networks whose morphology is characteristic of formation by liquid water. Further evidence that Mars is rich in water includes patterned ground and topographical features which suggest the fluid flow of soil material indicating near-surface ice. The presence of these fluvial features is a puzzle because liquid water is unstable on the present Mars primarily because the total atmospheric pressure is close to (and sometimes below) the triple point pressure of H_2O.

Figure 4-1. An outflow channel (Ravi Vallis) located at 1°S 42°W. The channel is 20 km across and appears to originate full-born from the enclosed region of chaotic terrain. These channels are thought to have been formed by the rapid release and flow of large quantities of water, thereby suggesting that Mars does have a significant inventory of water. Such channels could form under current climatic conditions.

The outflow channels and the valley networks provide two complimentary pieces of information about water on Mars. As illustrated by the size of the outflow channel in figure 4-1, these features are indicative of large-scale fluvial processes that must have been caused by catastrophic flooding events. They may have been caused by the rapid drainage of ice-dammed underground reservoirs. The rush of water under these conditions is such that these features could form even under the current Martian climatic conditions. To form these systems, large amounts of liquid water must have flowed on the Martian surface. The fluvial erosion indicated in the outflow channels implies a layer of water on Mars from 0.5 to 1 km thick.

On the other hand, the valley networks (fig. 4-2) appear to have been caused by gradual erosion due to slowly running water. Many of these channels could have been caused by the melting of ground ice or the release of groundwater. However, the dendritic drainage systems often associated with the valley networks could indicate rainfall. From the size and length of some of these networks it is clear that water must have been fairly stable at the surface. The valley networks are commonly found in the ancient cratered terrain in the southern hemisphere, generally thought to be the oldest Martian terrain, and are rarely found on the younger northern plains. This would suggest that the networks are old; they are believed to have formed primarily during, and shortly after, the decline in impact rates some 3.8 billion years ago. However, there is some fragmentary evidence to suggest that small, water-carved channels have been formed periodically throughout Martian history. The source of the water for these drainage systems is not clear: rainfall, glacial melt, and groundwater have been suggested.

Figure 4-2. Runoff and dendritic channel. The runoff channel, Nirgal Vallis (top panel), located at 28°S, 40°W, is 800 km long and looks different from rivers on Earth because of the open nature of the network and the lack of a large catchment area; such channels probably derive from groundwater sapping rather than surface runoff. Dendritic channels (bottom panel) found in the ancient terrain are most probably formed by surface runoff following precipitation. The craters overlying the channels indicates that these features formed about 3.8 billion years ago. Unlike the outflow channels (fig. 4-1), the runoff and dendritic channels were probably formed under a significantly warmer climate—presumably caused by a thicker atmosphere—than the present Mars. This evidence for the stability of liquid water in the Martian surface 3.8 billion years ago is the primary motivation for considering the possible origin of life on Mars.

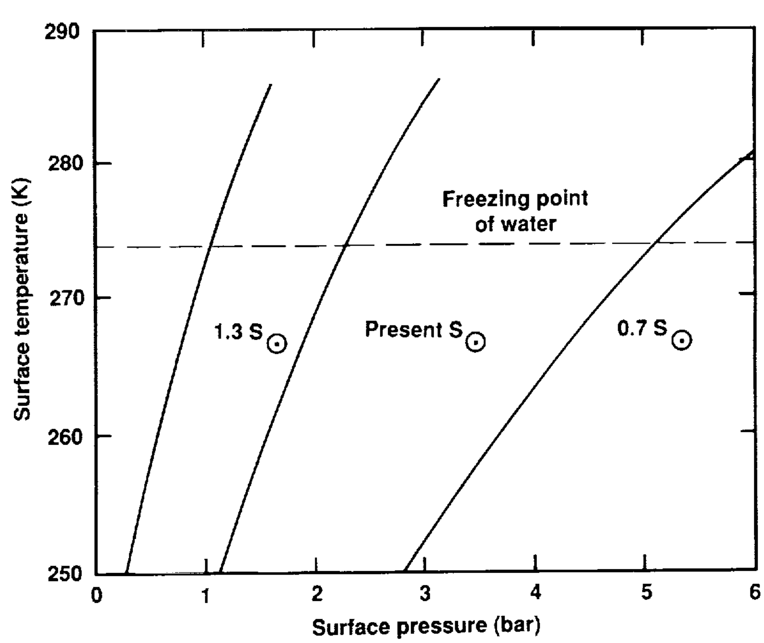
The sheer volume of water implied by the presence of outflow channels suggests that there was a significant amount of water on Mars and the long complex flow patterns of the valley networks indicate that, at some time, this liquid water was quite stable on the surface. While the amount of water present is unclear, it seems certain that there must have been aquatic habitats on early Mars. Water is the quintessence of life and the determination that there was liquid water on the surface of Mars for an extended period in its early history is the pivotal point upon which the discussion of a possible past Martian biota rests.

In order for liquid water to have freely existed on the surface of Mars in the past, conditions must have been quite different from the present. For liquid water to be stable, a thicker atmosphere would have been required with mean surface temperatures at or above freezing. Carbon dioxide is considered to have been the major constituent of the early Martian atmosphere, as it is in the present atmospheres of Venus and Mars. Similarly, it is believed to have been a major constituent in the early atmosphere of the Earth. Increased CO_2 in the atmosphere of early Mars could have provided the greenhouse effect required to keep the temperature above freezing even though the early Sun was 30% dimmer than at present.

A one-dimensional radiative-convective model of the early Martian atmosphere has been used to determine the amount of CO_2 required to raise the surface temperature above freezing, under the conditions of the faint early Sun. The calculations were based on an atmosphere composed of pure CO_2 in equilibrium with liquid water. The results, shown in figure 4-3, indicate that 5 bars of CO_2 were required to raise the globally and seasonally averaged surface temperature above the freezing point of water. At times of maximum eccentricity, one bar is required to raise the temperature above freezing at the equator at perihelion, producing seasonal meltwater.

It is possible that the mean temperature was below freezing and that only at certain places and during

Figure 4-3. Surface temperature as a function of CO_2 surface pressure. Globally averaged results are shown for the present level of sunlight and for faint early sun (30% reduction). Also shown is the result for the subsolar point on early Mars. These results suggest that about 1-5 bars of atmospheric CO_2 was required to raise the Martian surface temperature above freezing, as indicated by the fluvial features shown in figure 4-2.



certain seasons did temperatures rise above freezing. Valley networks could be formed while the mean temperature was many tens of degrees below freezing during seasonal warm periods. This suggestion is based on studies of the dry valleys of the Antarctic. The annual mean temperature in these valleys is -20°C, but the few days each year that the temperature is above freezing is adequate to form stream beds and ice-covered lakes. To have warmed only the perihelion subsolar point on the early Mars above freezing, presumably the warmest point and time on the planet, only 0.75 bars of CO_2 would have been required. Peak temperatures above freezing could have been maintained about 700 million years after the mean annual temperatures fell below freezing. Ice-covered lakes, such as those found in Antarctica, could have persisted during this interval.

If a thick CO_2 atmosphere was present on Mars, then it is reasonable to expect that there was a corresponding level of N_2. Estimates for the total amount of N_2 on early Mars range from 2 to 300 mb and, thus, cross the lower limit of N_2 pressure at which terrestrial organisms can incorporate N_2 by nitrogen fixation. The current partial pressure of N_2 of 0.2 mb appears to be well below the limit. Thus nitrogen, an essential macronutrient, was probably available on early Mars, but could have been a seriously limiting nutrient at later stages in the evolution of the atmosphere.

In addition to liquid water and a thicker atmosphere, Mars had much increased volcanism early in its history. The presence of volcanic events on early Mars may have played a key role in maintaining the environment as well as providing a habitat for early organisms. Mars, at present, is seismically and volcanically inactive when compared to the Earth, although there is ample evidence for tectonic and volcanic activity in the past. Most notable are the Tharsis Bulge and the large shield volcanoes, such as Olympus Mons (27 km above the mean elevation), which are found atop Tharsis. There is some evidence that volcanic activity has occurred, albeit at a reduced level, for most of Martian history. There is even the intriguing possibility that volcanism may have occurred in the Valles Marineris in geologically recent times.

The picture of the early climatic conditions on Mars that emerges from the previous discussion is one that is similar to early Earth: Both planets had liquid water on the surface, relatively thick CO_2–N_2 atmospheres, and volcanic activity. The presence of life early in Earth's history and the similarity between early Earth and early Mars thus motivates the question of early life on Mars.

As mentioned above, the conditions on the early Earth and early Mars were similar in many of the ecologically important parameters. A logical approach, then, to the question of possible past life on Mars is to investigate the history of early life on Earth. By looking at the record of early life on Earth we can develop concepts that may be applicable to life on early Mars and develop the tools to search the Martian sediments for fossil evidence of past life.

On Earth, life appears to have become widespread and to have developed sophisticated ecological communities by 3.5 billion years ago. Oxygenic photosynthesis by cyanobacteria may have even existed at this time. However, there is not general agreement as to when oxygenic photosynthesis developed. Pushing the origin of life further back into the geological past is difficult due to the scarcity of unaltered rocks of age 3.5 billion years and older. One intriguing set of sediments is found in Isua (Greenland) which dates back to 3.8 billion years ago. The organic material recovered from these sediments is also consistent with biological activity suggesting an even earlier origin for life. Thus, the time interval for the origin of life on Earth is between approximately 4.2 (the time of solidification of the mantle) and 3.5 billion years ago and life may have evolved over a much shorter time period.

To argue for the origin of life on Mars by analogy with the origin of life on Earth, the critical unknown is how long clement conditions prevailed after the first occurrence of liquid water on the Martian surface compared to the time required for life to have originated on Earth.

It has been suggested that the early thick Martian atmosphere was short lived. The fluvial features, particularly the valley networks, are evidence of a thick, moist early atmosphere. However, in this view, the atmosphere could not have been very thick for any significant period of time after 3.8 billion years ago. This argument is based upon the low levels of erosion, and the absence of infilling, of old post-bombardment surfaces and craters. Although erosion rates may have been larger before and just after the end of the early bombardment, they must have declined sharply with time. This is an important geomorphological argument *against* a thick, early Martian atmosphere lasting for many billions of years.

Mars would have lost its atmosphere as the CO_2 was transformed into carbonate rocks or was absorbed into the regolith. The timescale for eliminating atmospheric CO_2 by carbonate formation on early Mars is estimated to be a few times 10^7 yr. Thus, in the absence of recycling, the lifetime of a thick early atmosphere would have been very short indeed. On an active planet like the Earth, subduction of ocean sediments at plate boundaries followed by decomposition of carbonates in the mantle is the primary mechanism for completing the long-term geochemical CO_2 cycle. Mars does not have sufficient heat flow at present to cause the global scale recycling of volatiles incorporated into crustal rocks, nor is there any sign that Mars has, or ever had crustal dynamics akin to plate tectonics—rather its features are consistent with a 1-plate planet. Without these processes there appears to be no long-term geological mechanism on Mars to recycle CO_2-sink materials back into the atmosphere.

Perhaps intensive volcanism, driven by the high heat flows on early Mars, would have buried carbonate rocks to depths corresponding to their decomposition temperature, causing subsequent outgassing of CO_2, allowing for partial recycling. Eventually, as the interior of Mars cooled, the rate of volcanism would have been unable to recycle carbonates as fast as they were created, and the atmospheric pressure would have dropped. With this scenario, a thick moist CO_2 atmosphere could be retained for up to 10^9 yr, depending upon estimated values of the primordial heat flow and the total CO_2 budget on early Mars. Decomposition by impacts may have been a more effective mechanism for recycling carbonate rocks on early Mars. This mechanism would tie the existence of the thick CO_2 atmosphere to the impact history and would be consistent with the previously mentioned decline in erosion rate (and atmospheric pressure) after the end of the early bombardment.

It is also possible that Mars lost a considerable fraction of its early atmosphere as a result of erosion by high velocity impacts.

It was recently suggested that the flanks of Alba Patera contain channel features that are clearly of fluvial origin, and that the time of formation of these channels was well after the termination of the late bombardment on Mars. This implies these channels could not have formed as part of the putative warm, moist early epoch—which they presume to have lasted at most several hundred million years. Thus, features on Alba Patera must have formed under atmospheric conditions essentially similar to the present and this epoch of channel formation was due to mechanisms other than the presence of a thick, warm atmosphere. Hydrothermal processes are a likely candidate.

In summary, the geological evidence for stable liquid water and the atmospheric models developed to explain this stability together suggest that conditions on Earth and Mars may have been fundamentally similar, and that this period of similarity may have lasted for several hundred million years and perhaps for as long as $\sim 10^9$ yr or so. These time scales are comparable with the amount of time it took for life to have originated on Earth. Clearly, planetary evolution led to very different histories for the two planets after this initial period of similarity. Our current understanding of planetary evolution would suggest that the root cause of the unfavorable (to life) turn of events on Mars was the incorporation of its atmospheric CO_2 into carbonate sediments. The accumulation of carbonates was a direct and inevitable result of Mars' small size and, hence, its inability to support and retain sufficient heat flow to power plate tectonic activity and thereby recycle the atmospheric constituents in a long-term geochemical cycle.

As atmospheric CO_2 was deposited as carbonates, lowering the pressure and temperature, any liquid water present would have become ice-covered. On Earth, ice-covered lakes are found in the Antarctic dry valleys and maintain liquid water under perennial ice covers despite a mean temperature of –20°C (see fig. 4-4). One biologically important feature of an ice-covered lake is its capacity to provide a thermally buffered habitat in the underice water column despite the cold external temperature. Consequently, microorganisms are capable of growing in these thermally stable lakes in regions that are otherwise bereft of life. By analogy, it is possible that ice-covered lakes on early Mars provided a relatively warm, liquid water environment for early Martian biota long after the surface temperature fell below freezing. Another feature of perennially ice-covered lakes is their ability to concentrate atmospheric gases in the water column. For example, Lake Hoare, Antarctica, has about three times the oxygen and 50% more nitrogen than would be in equilibrium with the atmosphere. Both biological and abiological processes contribute to the enhanced gas concentrations. Sedimentation and loss through the

Figure 4-4. Lake Vanda, one of many perennially ice-covered lakes in the dry valleys of Antarctica. Despite mean temperatures of −20°C there is a persistent liquid water habitat under the ice cover of these lakes. The existence of ice-covered lake environments on early Mars may have considerably extended the period of potential biological activity after the mean surface temperature fell below freezing.

ice cover of organic carbon produced through photosynthesis represents a biological source of oxygen. Also, the incoming melt streams carry dissolved air into the lake. The gas is concentrated when the water freezes to the bottom of the ice cover. Both of these processes help to control the gas concentration in the lake water. These concentration mechanisms may have operated in the ice-covered Martian paleolakes, possibly enhancing the concentrations of biologically important gases (e.g., CO_2, N_2) from the thin Martian atmosphere. Thus as climatic conditions deteriorated on early Mars, ice-covered lakes could have been one of the last refuges—providing both thermal stability against a cooling external environment and enhanced gas concentrations of CO_2 and N_2 against a thinning atmosphere.

The formation of ice-covered lakes and the biota that may have inhabited these lakes is relevant to the question of continued carbonate precipitation on Mars after the mean surface temperatures fell below freezing. In lakes and shallow water environments on Earth, the presence of microorganisms accelerates the precipitation of carbonate by the removal of CO_2 from the local environment which lowers the pH. For this reason microbial mats and other benthic microflora are often encrusted in carbonate deposits. The presence or absence of organisms in Martian lakes could have been an important factor in setting the rate of carbonate deposition on early Mars.

Sediments deposited in lake environments may be identified from orbit or from the surface by the detection of stratified geological formations. The possible paleolake deposits on Mars detected from Viking orbiter imaging are therefore prime sites for a search for fossil evidence of past Martian life. The accumulation of detrital material and sediment on a lake bottom provides a fossil record spread over a large contiguous area. Although the shores may provide better sampling sites, there would be a good chance of detecting fossil remnants in sediments taken from anywhere on the lake bed. The possibility that carbonate formation was associated with aquatic environments on early Mars suggests that sites at which carbonate-bearing sediments are detected are prime locations for searching for organic material and/or biological fossils. Samples collected from depth could be analyzed for organic material and precipitates such as carbonates using pyrolysis techniques with analysis of the evolved gases.

Based upon the availability of liquid water on the Martian surface, the geological history of Mars can be divided into four epochs. In Epoch I, during which a primordial CO_2 atmosphere was actively maintained by impact and volcanic recycling, the mean annual temperature would have been above freezing, the pressure would have exceeded one atmosphere, and liquid water would have been widespread. Under such conditions, similar to early Earth, life could have arisen and become abundant. After this initial period of recycling, atmospheric CO_2 was irreversibly lost due to carbonate formation and the pressure and temperature declined. In Epoch II, the mean annual temperature fell below freezing, but peak temperatures would have exceeded freezing. As discussed above, ice-covered lakes, similar to those in the McMurdo Dry Valleys of Antarctica could have provided a habitat for life. In Epoch III, the mean and peak temperatures were below freezing and there would have been only transient liquid water. Microbial ecosystems living in endolithic rock "greenhouses" could have continued to survive. Finally, in Epoch IV, the pressure dropped to near the triple point pressure of water and liquid water could no longer have existed on the surface and life on the surface would have become extinct.

To explore the paleobiology of Mars many of the techniques and approaches that have been developed in the study of Earth's earliest biosphere can be applied. Finding evidence of past life on Mars will involve searching for many things, including direct traces of life such as microfossils, organically preserved cellular material, altered organic material, morphological microstructures and chemical discontinuities associated with life, isotopic signatures due to biochemical reactions, inorganic mineral deposits attributable to biomineralization, and hydrated minerals such as clays. Based upon our knowledge of fossils from Earth's Precambrian Era we can identify the types of targets that would be of paleobiological interest on future Mars missions. Figure 4-5 shows a diagram of the physical features that may be indicative of life in or near a lake environment. The sizes of these features range from micrometers to thousands of kilometers.

One of the most important forms of fossil evidence for microbial life on early Earth is stromatolites (fig. 4-6). These are defined as organosedimentary structures produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolism of microorganisms. Their formation is typically associated with the phototaxic properties of cyanobacteria and algae. The requirement for light drives these phototrophic organisms to move above any sediment that is deposited upon them leaving behind a layer of organic-rich sediment. In the absence of metazoan grazers, this sediment-building mechanism results in the formation of stromatolites. It is reasonable to suppose that if life arose on Mars, then the shallow water habitats would have been populated by algae-like photoautotrophs.

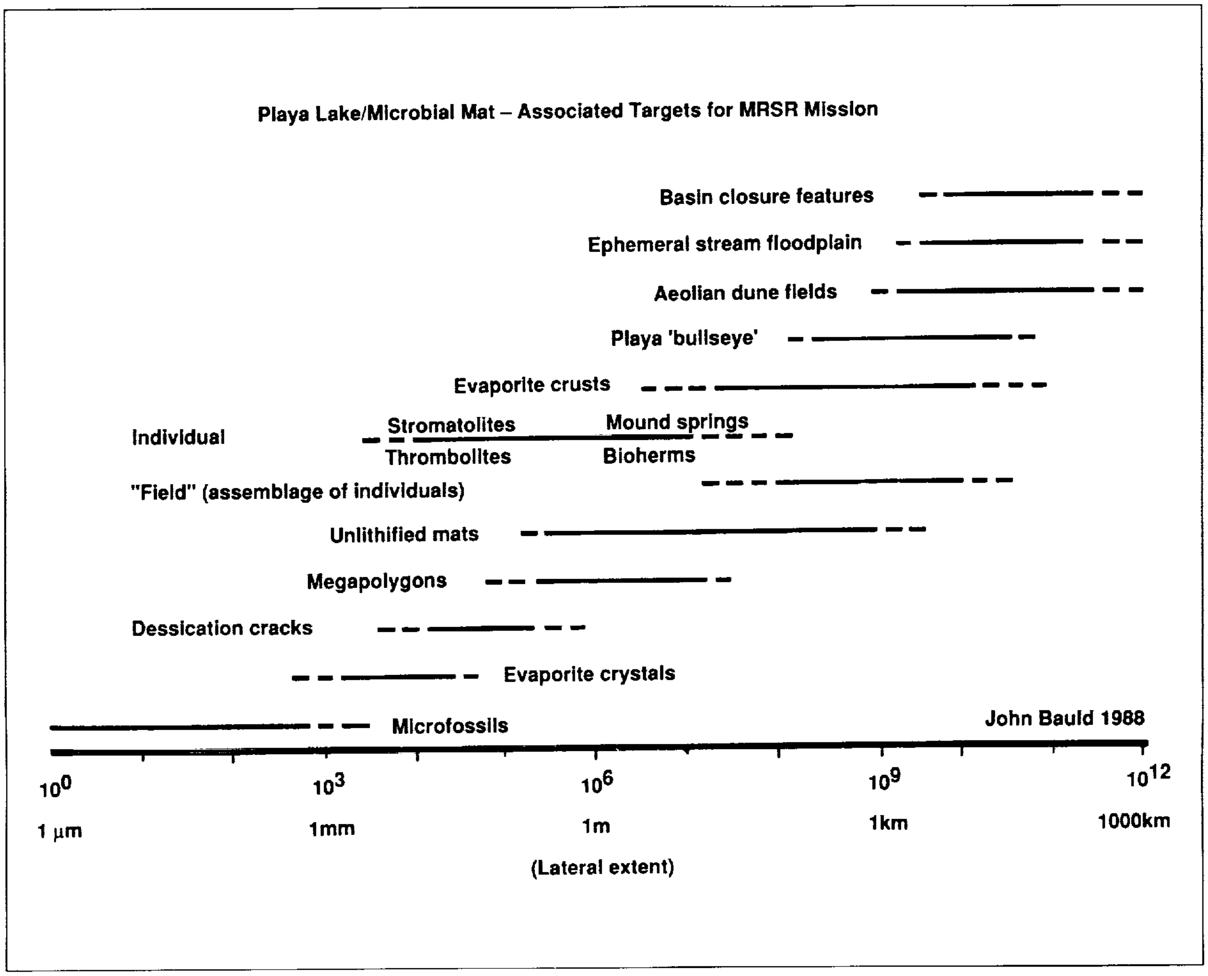


Figure 4-5. Approximate dimensions of biogenic and environmental targets diagnostic of, or consistent with, the former presence of saline/playa lake-hosted microbial mat communities on Mars. The search for fossil evidence of past life on Mars would begin with the investigation of such targets based upon orbital data.

Certainly it would appear that CO_2 was available on early Mars as a source of C atoms to any photoautotrophic organisms that may have existed to consume it. The prediction that stromatolites may be found on Mars is not just a reflection of our inevitably geocentric perspective on life. Rather, it springs from the fact that light is the most abundant source of energy on a planet and that motion toward light, through obscuring sediments, would have a selective advantage for those organisms that utilize it. Since stromatolites are macroscopic structures, often tens of meters in size, they are good targets for an *in situ* (and possibly remotely from orbit) search for fossil evidence of Mars' earliest biosphere.

Many of the techniques used to study early life on Earth may be applicable to the corresponding study on Mars. An interesting example of a powerful isotopic technique

Figure 4-6. A picture of a precambrian stromatolite, 2.6 billion years old. Stromatolites are sedimentary structures formed as microorganisms move up through infalling sediments to reach the light. These macroscopic fossils of early life may be found on Mars. (Photo courtesy of M. Schidlowski.)

used on Earth is shown in figure 4-7. This plot shows the isotopic composition of carbon in sedimentary carbonate and organic material over most of Earth's history. Also shown are the isotopic shifts due to contemporary autotrophs. The approximately 2% shift in carbon isotopic composition in organic material is due to the selectivity of the carboxylase enzyme for the lighter isotope of carbon, ^{12}C. In studies of Earth's earliest biosphere this isotopic shift provides a useful test for determining if organic matter is of biological origin. It may be the case that similar effects may be present on Mars and might be a useful diagnostic of biological origin. Alternatively it may be possible that life on Mars exhibits no characteristic carbon isotope shift. Abiotic synthesis produces a variation of isotopic composition with carbon-number of the product and also varies with the method of synthesis. A uniform isotopic shift is more likely to be of biological origin.

Fossil evidence of early life on Mars may also be found frozen in the permafrost regions that are thought to cover both the northern and southern hemispheres of Mars poleward of about 40°. The most likely current location of the bulk of the waters on Mars is as permafrost in the polar latitudes. In addition to the above theoretical arguments for permafrost ice on Mars, there is some geomorphological evidence as well. The equatorial regions on Mars appear to be depleted in ground ice while evidence for ground ice, in the form of quasi-viscous relaxation of topography due to creep deformation of ice, is widespread at high latitudes. Ground ice can exist in equilibrium with the atmosphere only at those latitudes and depths where crustal temperatures are below the frost point. Outside these regions, ground ice can survive only if it is diffusively isolated from the atmosphere by a regolith of low gaseous permeability.

The age of the Martian permafrost is uncertain, but it can be broadly classified, based upon crater densities. In the northern hemisphere there are plains with low crater densities which seems to indicate that they are of recent age (younger than 2 billion years old). In the southern hemisphere the terrain is heavily cratered, essentially dating back to the end of the late heavy bombardment some 3.8 billion years ago (the stratigraphic period designated as the Noachian).

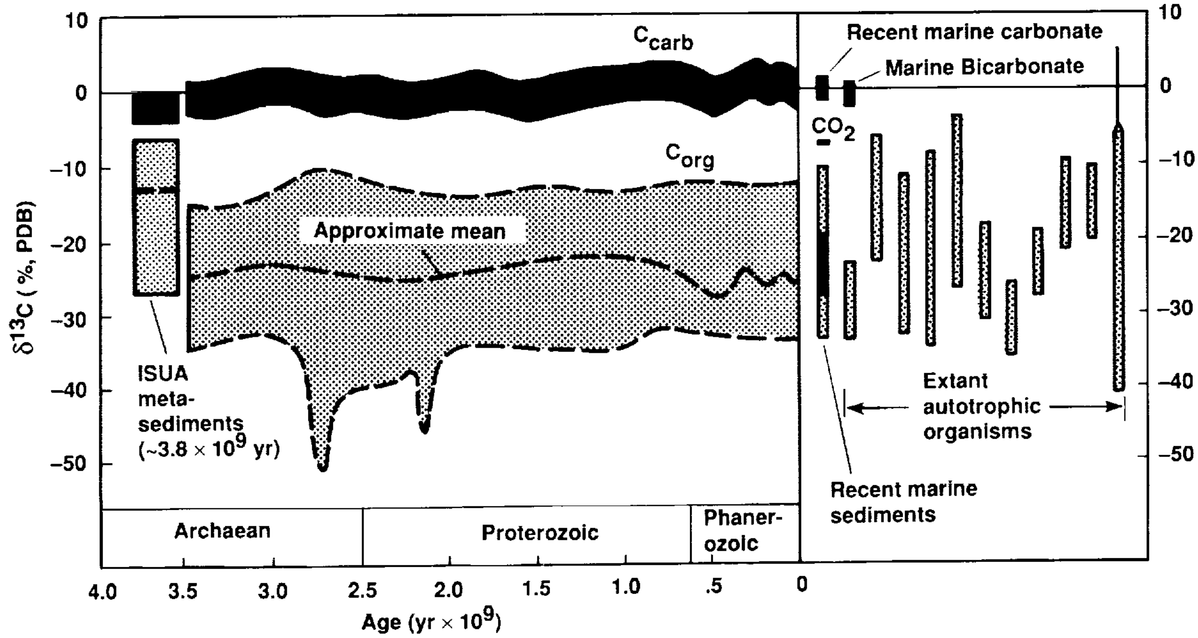


Figure 4-7. Carbon isotopic values for carbonate and organic sediments on Earth for the last 3.8 billion years. Carbon isotope values are reported in units of °/∞ which corresponds to the enrichment of the heavy isotope ^{13}C in parts per thousand, when compared to a standard. Photosynthetic systems preferentially uptake ^{12}C over ^{13}C resulting in a isotopic shift of about –25 °/∞. This isotopic shift has characterized organic sediments throughout Earth's history despite significant changes in the Earth's environment and biota. Similar carbon isotope values in ancient Martian organic material may be an indicator of biological origins.

As is the case on Earth, even as mean global temperatures on Mars were above freezing, polar permafrost could form and persist over geological times. Thus, material deposited, and preserved in the ancient permafrost regions of the southern hemisphere, should record events (and biota if any) that existed on Mars during the time that global conditions may have been suitable for life.

Material trapped within the permafrost of Mars should be exceptionally well preserved. The mean annual temperature of the permafrost regions is less than 200 K (–73°C) and material below several meters of depth would be well shielded from the cosmic radiation environment. The Martian climate of the past 3 billion years, while unsuited for life, is ideal for the preservation of frozen samples. In addition, the low erosion and burial rates (estimated to be about 1 meter/billion years) and the virtual absence of plate tectonics imply that the ancient material is accessible from the surface and has not been altered by internal heat or tectonic activity. Thus, we suggest that Martian permafrost may provide an ideal target for future exobiological investigations of Mars.

The discovery of fossil evidence of past life on Mars would have significant implications—so, too, would the determination that life did not originate on Mars. Our understanding of the processes that lead to the origin of life on Earth are uncertain at best and we do not know if life is a singular event or if it is widespread in the universe. Some theories of the formation of life in the cosmos would suggest that life is widespread. Finding evidence for past life on Mars would be a crucial confirmation of that hypothesis—the first data point other than Earth life. If detailed investigations of sediments on Mars confirm the view that there was a similarity between early Earth and early Mars, and yet life did not evolve on Mars, it may be an indication that the origin of life is a far more exacting process that we currently envision and is therefore far less widespread in the cosmos.

If life did evolve on Mars, as it did on the Earth, a better record of these events may be preserved in the sediments of Mars than is available on Earth. On Earth unaltered rocks that date back to the 3.5–4.0-billion-year-old timeframe are rare, while on Mars over half of the planet (primarily the southern hemisphere) dates back to the end of the late bombardment, some 3.8 billion years ago. Thus, while there may be no life on Mars today, it may hold the best record of the events that led to the origin of life on Earth-like planets. Mars still holds much interest from a biological perspective.

Additional Reading

Baker, V. A.: The Channels of Mars. University of Texas Press, Austin, 1982.

Banin, A.; and Rishpon, J.: Smectite Clays in Mars Soil: Evidence for their Presence and Role in Viking Biology Experimental Results. J. Molecular Evol., vol. 14, 1979, pp. 133-152.

Bauld, J.: In Exobiology and Future Mars Missions, C. P. McKay and W. Davis, eds. Abstracts of workshop held March 1988.

Biemann, K.; Oro, J.; Toulmin, P. III; Orgel, L. E.; Nier, A. O.; Anderson, D. M.; Simmonds, P. G.; Flory, D.; Diaz, A. V.; Rushneck, D. R.; Biller, J. E.; and LaFleur, A. L.: J. Geophys. Res., vol. 82, 1977, pp. 4595-4676.

Biemann, K.: The Implications and Limitations of the Findings of the Viking Organic Analysis Experiment. J. Mole. Evol., vol. 14, 1979, pp. 65-70.

Calder, J. A.; and Parker, P. L.: Geochemical Implications of Induced Changes in ^{13}C Fractionation by Bluegreen Algae. Geochem. Cosmochem. Acta, vol. 37, 1973, pp. 133-140.

Campbell, S. E.: Precambrian Endoliths Discovered. Nature, vol. 299, 1982, pp. 429-431.

Carr, M. H.: The Surface of Mars. Yale University Press, New Haven, Conn., 1981.

Carr, M. H.: Stability of Streams and Lakes on Mars. Icarus, vol. 56, 1983, pp. 476-495.

Carr, M. H.: Mars: A Water-Rich Planet. Icarus, vol. 68, 1986, pp. 187-216.

Kahn, R.: The Evolution of CO_2 on Mars. Icarus, vol. 62, 1985, pp. 175-190.

McKay, C. P.; and Nedell, S. S.: Are There Carbonate Deposits in Valles Marineris, Mars? Icarus, vol. 73, 1988, pp. 142-148.

Pollack, J. B.; Kasting, J. F.; Richardson, S. M.; and Poliakoff, K.: The Case for a Wet, Warm Climate on Early Mars. Icarus, vol. 71, 1987, pp. 203-224.