

THE EARLY ENVIRONMENT AND ITS EVOLUTION ON MARS: IMPLICATIONS FOR LIFE

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Abstract. There is considerable evidence that the early climate of Mars was very different from the inhospitable conditions there today. This early climate was characterized by liquid water on the surface and a dense atmosphere composed predominantly of CO₂. The duration of these warm initial conditions on the surface of Mars is uncertain, but theoretical models suggest that they could have persisted for hundreds of millions up to a billion years. From studies of the Earth's earliest biosphere we know that by 3.5 Gyr ago, life had originated on Earth and reached a fair degree of biological sophistication. Surface activity and erosion on Earth make it difficult to trace the

history of life before the 3.5-Gyr time frame. If Mars did maintain a clement environment for longer than it took for life to originate on Earth, then the question of the origin of life on Mars follows naturally. The fossil evidence of early life on Earth provides clues as to what form fossils on Mars might take. Of particular interest are stromatolites, macroscopic layered structures that result from the anchoring of sediments by microorganisms living in the photic zone. Since over two thirds of the Martian surface is more than 3.5 Gyr old, the possibility exists that Mars may hold the best record of the events that led to the origin of life, even though there may be no life there today.

INTRODUCTION

Early in its history, conditions on Mars may have been suitable for the origin of life. Studies of hardy terrestrial ecosystems, coupled with both climatological and geological studies of Mars and paleontological studies of early life on Earth, have resulted in the emergence of new scientific interest in the possibility of the origin of life on Mars. In this paper we review the recent developments in this area and indicate areas of future research. We also consider the role that upcoming missions to Mars may play in testing current speculation about the emergence of life on a more clement primordial Mars.

Over the past 10 years, detailed studies of the results from the Viking and Mariner missions to Mars have provided convincing evidence that liquid water was present on early Mars and thus that early Mars was warmer and the atmospheric pressure was considerably higher than at present. In addition, studies of Earth's earliest biosphere have suggested a close coupling between the evolution of early life forms and the physical and chemical evolution of the planetary surface. From a biological perspective, there were many similarities between early Earth and early Mars [McKay, 1986]. This, combined with the prospect that the clement conditions on primordial Mars could have existed over time scales comparable to the origin of life on Earth, has led to a convergence of research effort in the areas of early climate and life on Mars.

Currently, Mars is a cold desert planet, inhospitable to life as we know it. The major components of the atmosphere are 95% CO₂, 2.7% N₂, and 1.6% Ar [Owen *et al.*, 1977]. The surface pressure as recorded by the Viking 1 lander varies from 9 to 7.5 mbar [Hess *et al.*, 1979, 1980] as a substantial fraction of the atmospheric CO₂ freezes onto the winter polar caps. The mean annual surface temperature is 215 K, insuring that most water on the surface remains in a permanently frozen state. The Martian atmosphere contains only a few precipitable microns of water vapor [Jakosky and Farmer, 1982], consistent with the low temperatures.

The Viking landers carried experiments specifically designed to search for signs of microbial life on Mars. Interpretation of the results of the Viking biology experiments has been controversial, but most investigators would suggest that they do not indicate biological activity at the landing sites [see Klein, 1978, 1979; Horowitz, 1986] (for an opposite view, see Levin and Straat [1981] and Levin 1988]).

Studying the relationship between planetary evolution and the appearance of life (i.e., exobiology [see Lederberg, 1960; DeVincenzi, 1984]) is an interdisciplinary task requiring strong interaction between geophysical and biological elements. The study of early life on Mars is rooted in the geophysical understanding of Mars and its past history. Hence theories of biological or chemical evolution on Mars must be based upon a geophysical

understanding of the history of the Martian environment. By the same token the intriguing questions posed by the exobiological perspective provide specific inputs to the program of geophysical exploration of Mars. This interaction will, in the long run, benefit our overall understanding of planets and life.

Current hypotheses for the origin of life (based upon the work of *Oparin* [1924, 1936] and *Haldane* [1928]; for a modern review, see *Miller and Orgel* [1974]) postulate that life on Earth began with the abiological production of the organic materials from which all life on Earth is composed. This prebiological stage in the origin of life is called "chemical evolution," a term which shall here encompass important variations on the purely organic chemical evolution theme, most notably the clay-life hypothesis [*Cairns-Smith*, 1982]. In the broadest sense, chemical evolution constitutes those nonbiological chemical events that lead to the origin of biological life.

Even if life never evolved on Mars, exobiology would be well served if the study of that planet's past and present environments furthered our understanding of chemical evolution and the events that led to the origin of life on Earth. Thus the study of Mars' environmental conditions, including the distribution and cycling of the biogenic elements (C, H, N, O, P, S) and their components (H_2O , CO_2 , NO_x , etc.), the distribution and destruction of organic matter and the presence of carbonates, clay and other water-related minerals and sediments, is relevant to the understanding of chemical evolution on Mars. These goals continue to be of very high priority for exobiology studies on future Mars missions.

It is possible that chemical evolution led to the origin of life on Mars. On Earth the unequivocal evidence for life dates to 3.5 Gyr ago. By this time there was already a fair degree of biological sophistication (see, for example, *Awramik et al.* [1983] and *Schopf* [1983]), suggesting that life evolved much earlier. If the early environment on Mars was similar in temperature, water abundance, and atmospheric composition to that on the early Earth, and if this similarity persisted over the time period in which life evolved on Earth, then life may have evolved on Mars during the same period. Furthermore, if the environment played a strong role in determining the form life assumed, these life forms may have been similar to those living on Earth 3.5 Gyr ago and before. The search for the fossil evidence of this past life would be a major challenge for future exploration of Mars, with both robotic and human missions.

If life did evolve on Mars at some time in the past, is it a foregone conclusion that this life is now extinct? Although the present conditions on Mars are not at all favorable to Earth-type life, the question of extant life on Mars is, strictly speaking, still open. Spacecraft exploration of Mars has proven that life is not widespread or obvious on the surface of Mars. However, the data do not rule out the

possibility that remnants of an early Martian biota could still exist in microhabitats confined in space and/or time. A better knowledge of the present environment of Mars over global and seasonal scales is required to reduce this uncertainty.

The progression of the evolution of possible life on Mars can be summarized as follows: chemical evolution leading to the origin of life, the evolution of this early life, and subsequent developments leading either to extinction or to retreat into transient microhabitats. To understand the potential for the origin of life on Mars and assess the likelihood of its occurrence, we must first understand the geophysical evolution of the planet.

GEOPHYSICAL HISTORY OF MARS

Our knowledge of the geological and climatological history of Mars, while still incomplete, has increased enormously as a result of spacecraft imaging of the surface and in situ data from the Viking landers. In this section we briefly review the geophysical history of Mars with particular emphasis on those aspects that are relevant to exobiology. These aspects are initial atmospheric mass and composition, evidence for liquid water, evolution of climate, and volcanic history.

The Early Mars Atmosphere: Volatile Abundances

Current Mars is cold and dry, and the atmospheric pressure is low. The initial complement of volatiles on Mars is uncertain, but there is strong evidence that water, carbon dioxide, and nitrogen were more abundant in the early Martian atmosphere than at present. Arguments for the origin of life on early Mars rely heavily on the hypothesis that conditions on early Mars were more clement than at present. This would have been the case if there was significant greenhouse warming of the planet due to the presence of a dense early atmosphere. In this section we review the evidence for the initial complement of outgassed volatiles which may have resided in the atmosphere of early Mars. In subsequent sections we examine how these volatiles may have been lost to the atmosphere and how long clement conditions may have lasted.

Various estimates have been made of the total inventory of atmospheric volatiles, including water, CO_2 , and N_2 on Mars. Table 1 shows a representative sample of estimates for the total outgassed inventory of biologically significant volatiles as compared to the present Martian atmosphere. As is evident from Table 1, a variety of techniques have been used to estimate Mars' volatile inventory, with widely varying results.

Theoretical models of planetary formation [e.g., *Lewis*, 1972] predicted that Mars should be more volatile-rich

TABLE 1. Mars Total Volatile Inventory

	CO_2 , mbar	N_2 , mbar	H_2O , *m	Note
Present Mars atmosphere	~ 10	0.2	~ 7†	atmosphere only
Earth scaling‡	27,000	300	1,200	equal volatiles, gram/gram
Rasool and LeSargeant [1977]	198	3.1	5.9	^{36}Ar , ordinary chondrites
Anders and Owen [1977]	140–525	2–8	9.4	K, ^{40}Ar , ^{36}Ar / ^{40}Ar
McElroy et al. [1977]	1,760	21.5	133	^{14}N / ^{15}N
Clark and Baird [1979]	187–410	8.6	88	^{40}Ar , "excess volatiles"
Pollack and Black [1979]	1,000–3,000	6.6–66	80–160	N, noble gases, Venus data
Carr [1986]	10,000–20,000	100–300	500–1,000	geomorphology
Dreibus and Wänke [1987]	3,000§	33§	130	SNC meteorites, Martian Cl
Greeley [1987]	>1,000§	>11§	>45	volcanism only

*Water estimate cited as thickness of a layer of water spread over the entire surface of Mars.

†Value in microns.

‡Determined by assuming that the Martian ratio of volatiles of per gram planet is the same as the Earth's. Earth volatiles are based upon Turekian and Clark's [1975] values of CO_2 : 190 bars, N_2 : 2 bars, and H_2O : 3200 m.

§Values not from referenced source but determined assuming that the ratios of volatiles are the same as the Earth scaling result.

than Earth since it formed farther from the Sun. However, geochemical models based upon the observed isotopic ratios and noble and other indicator gas abundances in the present Martian atmosphere [e.g., McElroy et al., 1977; Anders and Owen, 1977; Rasool and LeSargeant, 1977; Pollack and Black, 1979, 1982] or upon the elemental composition of the soil [Clark and Baird, 1979] all suggested that Mars is volatile-poor when compared to Earth. Dreibus and Wänke [1987] based their estimate of water abundance on an analysis of the Shergottites, Nakhilites, and Chassignites (SNC) meteorites, which are thought to have come from Mars (see, for example, Becker and Pepin [1984] and Pepin [1987]; but see also Bogard and Johnson [1983]). Greeley [1987] calculated the amount of water that would have been released by the observed volcanic features by assuming that 1% is the water content of Martian magma, determined primarily by Earth analog studies. Since this method does not account for water released by means other than volcanism, his estimate places a lower limit on the total water content.

The most direct way to estimate the amount of water that was present on early Mars is to use the geomorphological evidence that dates back to this period of Martian history. This was the approach used by Carr [1986], who determined the amount of water that must have flowed through the Valles Marineris system in order to create the observed channel features. He obtained a lower limit by assuming maximal efficiency for erosion by the flowing water. By extrapolating these results to the rest of the planet, he inferred that Mars has outgassed between 0.5 and 1 km of water. Clearly, Carr's [1986] estimate for the outgassed water inventory would imply that Mars is volatile-rich, with a volatile endowment comparable to Earth's (Table 1).

All estimates of the initial complement of volatiles are greater than the abundance of water, CO_2 , and nitrogen currently residing in the atmosphere of Mars (Table 1).

The current loss rate of volatiles due to atmospheric escape is insufficient to deplete the initial endowment of water and other volatiles, and most of the volatiles may still be on the planet in surface reservoirs. If the current rate of atmospheric escape has remained constant for water (as 2H and O) at $6 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ [Liu and Donahue, 1976; McElroy et al., 1977] and N_2 at $5.6 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ [Fox and Dalgarno, 1983], the total loss over the past 4.5 Gyr would be 2.5 m of water and 1.4 mbar of N_2 . Recently, Owen et al. [1988] have reported a D/H ratio on Mars of $(9 \pm 4) \times 10^{-4}$, which is enriched over the telluric value by a factor of 6, indicating that a significant fraction of the exchangeable water has been lost to space. This implies either much higher escape rates in the past or that the initial complement of water on Mars was very small, no more than a few meters [Yung et al., 1988]. However, the published error bars on the observations of Owen et al. [1988] are too large to permit a unique estimate of the initial water inventory [see Yung et al., 1988].

It is clear from Table 1 and the previous discussion that the complement of volatiles on early Mars and their subsequent fate is highly uncertain. This uncertainty impacts heavily on whether or not life could have originated on Mars and survived for any geologically significant period of time. If the upper range of estimates for volatiles is accurate, then warm climatic conditions would have prevailed, and the origin of life may have occurred. If the lower range of the estimates is accurate, it is unlikely that conditions would ever have been conducive to the origin of life. This is an important area in which better information is needed to evaluate the possibility of life on Mars.

Liquid Water on Early Mars

Water is the quintessence of life on Earth. The geological evidence that liquid water was abundant on the Martian surface in the past is probably the most significant



Figure 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.

ecological fact we currently know about Mars. Yet liquid water is unstable on present Mars primarily because the total pressure is close to (and sometimes below) the triple-point pressure of water [Ingersoll, 1970; Kahn, 1985]. For liquid water to have remained stable in the past, as indicated by widespread fluvial networks, the atmospheric pressure must have been higher than at present and surface temperatures must have remained above freezing for at least part of the year. Thus conditions on early Mars were more conducive to life than they are during the present epoch.

There is considerable geological evidence for the past presence of ground ice and liquid water on the surface of Mars (see reviews by Carr [1981, 1987] and Squyres [1984]). This evidence includes patterned ground and topographical features which suggest the fluid flow of soil material indicating near-surface ice [Squyres and Carr, 1986; Mouginis-Mark, 1987] (see Zimbleman [1987] and Schultz and Gault [1979] for cogent discussions of problems and ambiguities in these interpretations). The most compelling evidence for liquid water on Mars comes from the observations of fluvial features [Pieri, 1980; Carr and Clow, 1981; Carr, 1987, and references therein].

These include the outflow channels and valley networks whose morphology is characteristic of formation by liquid water.

The outflow channels, as shown in Figure 1, are large-scale fluvial features that appear to have been caused by catastrophic flooding events [Baker and Milton, 1974; Baker, 1982] possibly associated with the rapid drainage of ice-dammed underground reservoirs [Carr, 1979]. Although these features are thought to be ancient, their formation does not necessarily require a denser atmosphere because the rush of water associated with them is so intense [Wallace and Sagan, 1979; Carr, 1983].

In contrast to the outflow channels, valley networks could not form under current conditions of atmospheric pressure on Mars. The valley networks (Figure 2) appear to be dendritic drainage systems [Baker, 1982; Pieri, 1976, 1980] believed to have been caused by the slow erosion of running water. Some of the channels have complex dendritic networks leading into the main channel and are suggestive of formation by rainfall [Masursky et al., 1977]. From the length and size of some of these networks it is clear that water must have been fairly stable at the surface [Wallace and Sagan, 1979; Carr, 1983]. The valley

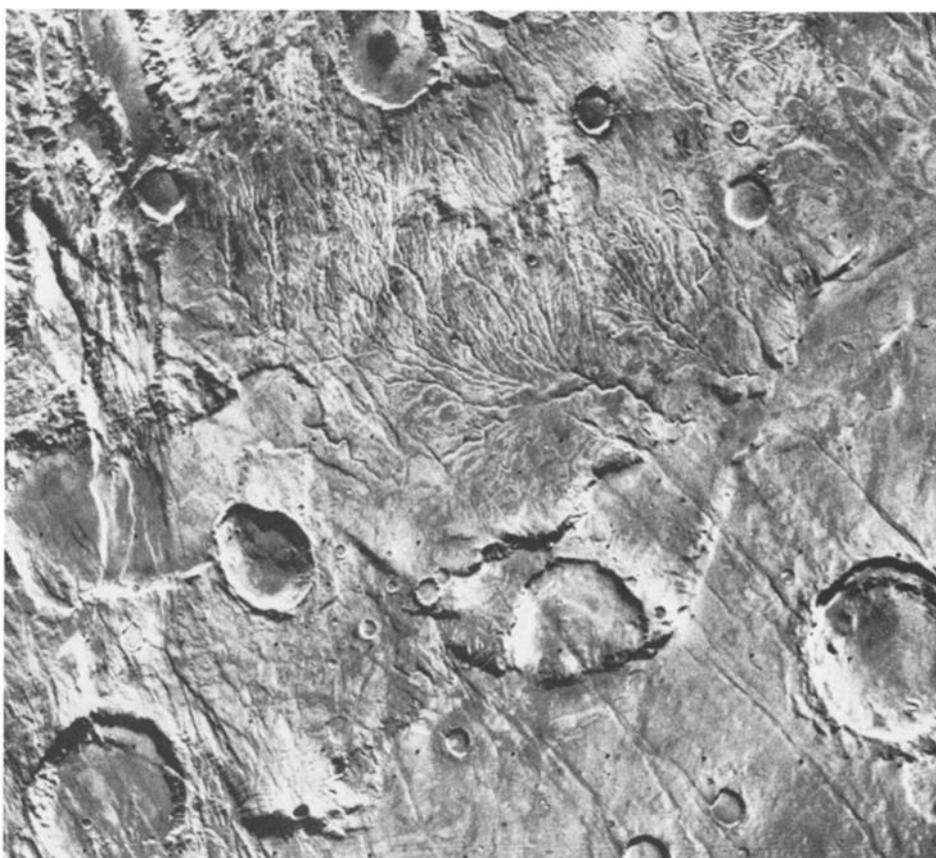
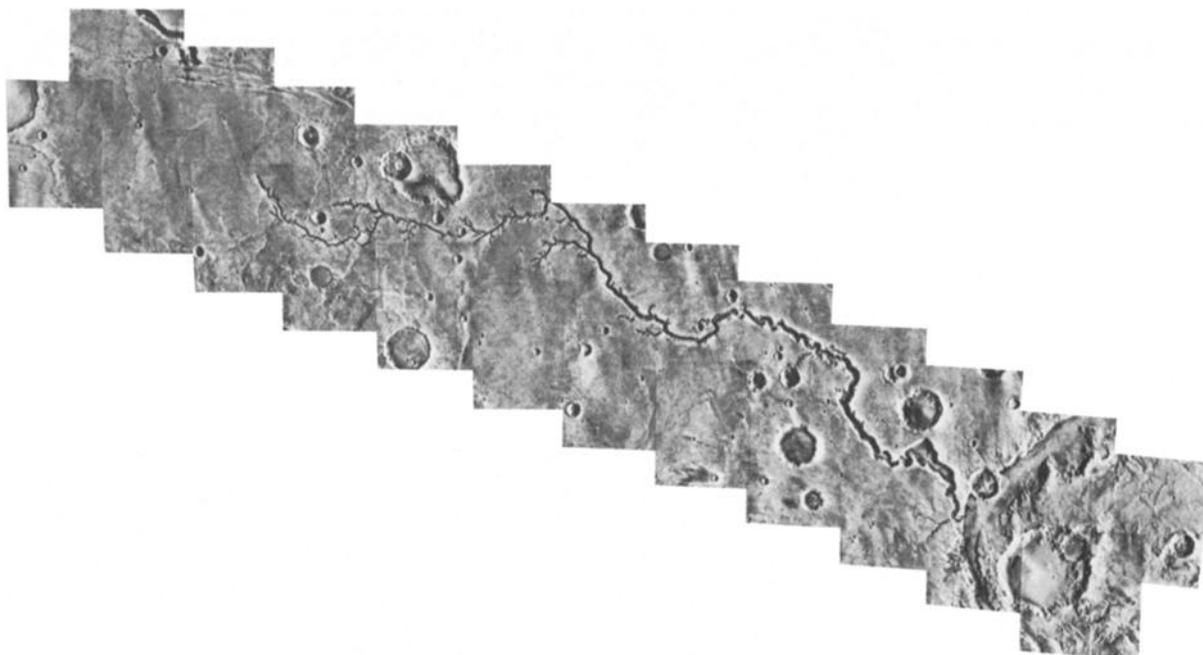


Figure 2. Runoff and dendritic channels. The runoff channels, such as (top) Nirgal Vallis, which is located at 28°S, 40°W, is 800 km long, and looks different from rivers on Earth because of the open nature of the network and the lack of a large catchment area, probably derive from groundwater sapping rather than surface runoff. (Bottom) Dendritic channels found in the ancient terrain are most probably formed by surface runoff following precipitation. The craters overlying the channels indicate that

these features formed about 3.8 Gyr ago. Unlike the outflow channels (Figure 1), the runoff and dendritic channels were probably formed under a significantly warmer climate, presumably caused by a denser atmosphere than on the present Mars. This evidence for the stability of liquid water on the Martian surface 3.8 Gyr ago is the primary motivation for considering the possible origin of life on Mars.

networks are commonly found in the ancient cratered terrain in the southern hemisphere, generally thought to be the oldest Martian terrains, and are rarely found on the younger northern plains [Carr, 1981]. This would suggest that the networks are old and are believed to have formed primarily during, and shortly after, the decline in impact rates some 3.8 Gyr ago [Carr, 1986]. However, there is some fragmentary geomorphological evidence to suggest that small water-carved channels have been formed periodically throughout Martian history [Masursky *et al.*, 1987]. The source of the water for these drainage systems is not clear; rainfall, glacial melt, and groundwater have been suggested (for reviews, see Carr [1981] and Baker [1982]).

Taken together, the outflow channels and the valley networks provide two complementary pieces of information about water on Mars. The size and extent of the outflow channels suggest that there was a significant amount of water on Mars [Carr, 1986], and the long complex dendritic systems of the valley networks indicate that at some time, liquid water was quite stable on the surface [Baker, 1982]. While the amount of water present is unclear, it seems certain that there must have been aquatic habitats on early Mars and that, at minimum, these habitats existed through 3.8 Gyr ago. This is the pivotal point upon which the discussion of a possible Martian biota rests.

The Early Martian Atmosphere

Although the details are not clear, the presence of fluvial features indicating the generation and gradual flow of liquid water on the Martian surface provides indirect evidence for a warmer, denser atmosphere on Mars with mean surface temperatures at or above freezing [Pollack, 1979; Pollack and Yung, 1980; Cess *et al.*, 1980; Hoffert *et al.*, 1981; Postawko and Kuhn, 1986; Pollack *et al.*, 1987].

Carbon dioxide is considered to have been the major constituent of the early Martian atmosphere, as it is in the present atmosphere. Similarly, it is believed to have been a major constituent in the early atmosphere of the Earth [Walker, 1977, 1985; Holland, 1984; Levine *et al.*, 1982a]. Increased CO₂ in the atmosphere of the Earth could have provided the greenhouse effect required to keep the temperature above freezing even though the early Sun was 30% dimmer than at present [Sagan and Mullen, 1972; Owen *et al.*, 1979; Kasting and Ackerman, 1986]. Similarly, increased CO₂ in the early Martian atmosphere may have provided the greenhouse effect necessary to keep Mars warm enough for liquid water to occur [Pollack *et al.*, 1987].

In order to estimate how much CO₂ would be required to warm the surface of Mars above the freezing point of water, Pollack *et al.* [1987] constructed a detailed

radiative-convective model of the early Martian atmosphere composed of pure CO₂ in equilibrium with liquid water, under the conditions of the faint early Sun. Their calculations, as illustrated in Figure 3, indicate that from 1 to 5 bars of CO₂ were required to raise the mean surface temperature above the freezing point of water. An atmosphere of 0.75 bar of CO₂ would have been required to have warmed only the perihelion subsolar point on early Mars, presumably the warmest point on the planet, above freezing [Pollack *et al.*, 1987]. It is possible to produce liquid water under conditions of lower temperature and pressure (see, for example, Ingersoll [1970], Kahn [1985] and Clow [1987]); however, production of the observed morphologies of some of the valley networks [Carr and Clow, 1981; Baker, 1982] would require that water flow over the surface for considerable distances. Such flow is much more difficult to sustain than localized production [Carr, 1983] primarily because of the high evaporation rates for liquid water under low atmospheric pressure conditions [Kahn, 1985]. Even if atmospheric pressures were high enough to allow liquid water to flow for significant periods of time, seasonal variability of temperature may have been important in forming valley networks; McKay and Nedell [1988] have pointed out that summertime maximum temperatures which exceed freezing for only a few days each year [Clow *et al.*, 1988] allow fluvial features to form from glacial meltwater in the Antarctic dry valleys on Earth despite a mean annual temperature of -20°C.

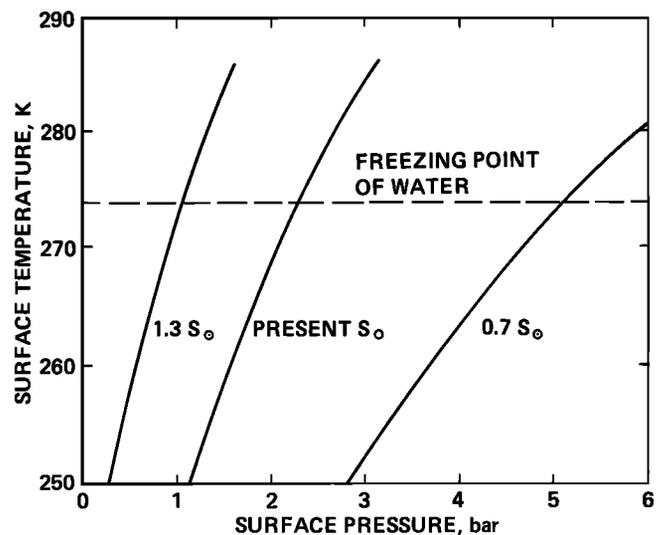


Figure 3. Surface temperature as a function of CO₂ surface pressure (adapted from Pollack *et al.* [1987]). Globally averaged results are shown for the present level of sunlight and for faint early Sun (30% reduction). Also shown is the result for the subsolar point on early Mars. These results suggest that about 1 bar of atmospheric CO₂ was required to raise the Martian surface temperature above freezing as indicated by the fluvial features shown in Figure 2.

Carbonate Formation and Duration of Clement Conditions on Mars

The critical unknown in gauging the possibility of the origin of life on Mars is how long clement conditions prevailed after the first occurrence of liquid water on the Martian surface. Eventually, Mars would have lost its dense CO₂ atmosphere as it was transformed into carbonate rocks (see for example, *Kahn* [1985], *Pollack et al.* [1987] and *McKay and Nedell* [1988]), was increasingly absorbed by the regolith as temperatures became cooler [*Fanale et al.*, 1982; *Zent et al.*, 1987], or reacted with surface materials [*Huguenin*, 1976]. Carbonate formation can account for the observed atmospheric pressure on present Mars [*Kahn*, 1985], which is close to the triple-point pressure of water vapor. Carbonate formation would have proceeded on Mars as long as liquid water occurred and ceased once the pressure dropped so low that liquid water could no longer form [see *Kahn*, 1985]. Carbonate rocks are formed when metallic ions, weathered from surface rocks, accumulate in liquid water. Atmospheric CO₂ dissolves in water and combines with cations such as Ca²⁺, Mg²⁺, and Fe²⁺ and subsequently precipitates from solution as carbonate minerals. On the basis of the Viking elemental analyses [*Toulmin et al.*, 1977; *Clark et al.*, 1982] the most likely carbonates to occur on Mars are CaCO₃ (calcite), MgCO₃ (magnesite), CaMg(CO₃)₂ (dolomite), FeCO₃ (siderite), and possibly MnCO₃ (rhodochrosite). Carbonates are thought to be stable under the present Martian environment [*Booth and Kieffer*, 1987; *Gooding*, 1978] (but see also *Clark and Van Hart* [1981]).

The time scale for decreasing atmospheric CO₂ from 1 bar to its present value by carbonate formation is estimated to be a few times 10⁷ years [*Kahn*, 1985; *Pollack et al.*, 1987]. Thus in the absence of recycling, the lifetime of a dense 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 CO₂ 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 one-plate planet [*Solomon*, 1978]. Without these processes there appears to be no long-term geological mechanism on Mars to recycle CO₂ sink materials back into the atmosphere.

Pollack et al. [1987] proposed an alternative mechanism to plate tectonics which could have recycled carbonates early in Martian history. 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 CO₂.

Eventually, as the interior of Mars cooled, the rate of volcanism would have failed to recycle carbonates as fast as they were created. Their results indicate that a dense CO₂ atmosphere could be retained for ~10⁹ years based upon estimated values of the primordial heat flow and the total CO₂ budget on early Mars. In fact, if the total inventory of CO₂ is in the 10- to 20-bar range (Table 1) as estimated by *Carr* [1986], an atmospheric lifetime in excess of 10⁹ years is strongly suggested. These scenarios are highly uncertain because the weathering rate of carbonates on Mars is unknown and must be scaled from Earth on the basis of an assumed value for the fraction of the surface covered with liquid water. The rates of early volcanism on Mars are similarly uncertain.

Carr [1989] has suggested an alternative mechanism to recycle carbonate rocks on early Mars: decomposition by crustal heating due to meteoritic impacts. *Carr* [1986] proposed that the entire atmospheric inventory of volatiles was outgassed on Mars before the decline in the impact rates 3.8 billion years ago. He considers the fluvial features, particularly the valley networks, as evidence for a dense moist early atmosphere. However, he contended that the atmosphere could not have been very dense for any significant period of time after 3.8 Gyr ago (see also *Carr and Clow* [1981]). This argument is based upon the low levels of erosion, and the absence of infilling, of old postbombardment surfaces and craters. Although erosion rates may have been greater 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 dense early Martian atmosphere lasting for many billions of years. Impact-related recycling of carbonates would tie the existence of the dense CO₂ 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. *Carr's* [1989] carbonate recycling mechanism would imply that the duration of a clement period which is warm enough to support widespread liquid water would be no more than a few hundred million years.

To date, there has been no direct detection of carbonates on Mars despite ground-based spectroscopic searches (see, for example, *McCord et al.* [1982] and *Singer* [1985]) and searches of past spacecraft data [*Roush et al.*, 1986; *McKay and Nedell*, 1988]. This may be simply due to the presence of a thin layer of aeolian dust that may cover the surface at the scales of the observations (typically hundreds of kilometers or more). However, carbonates have been detected in the SNC meteorites [*Gooding et al.*, 1988] that are thought to have originated on Mars.

McKay and Nedell [1988] have suggested that the sedimentary material in the Valles Marineris canyons could be formed by carbonate deposition. The amount of

carbonates required is equivalent to ~30 mbar of atmospheric CO₂. This result illustrates that carbonate precipitation could provide enough material to account for the layered deposits in the Valles Marineris [Nedell *et al.*, 1987]. It also suggests that many Martian canyons and playa basins must contain carbonates if upward of 1 bar of atmospheric CO₂ is sequestered as carbonates on Mars. The Mars Observer mission should yield more information on any near-surface deposits of carbonates.

There is exobiological importance to the detection of carbonates. In lakes and shallow-water environments on Earth the presence of microorganisms often causes the precipitation of carbonate by the removal of CO₂ from the local environment (see, for example, Golubic 1973, Wharton [1982], and Walter and Bauld [1983]). For this reason, microbial mats and other benthic microflora are often encrusted in carbonate deposits. Indeed, carbonate layers in lake sediments are often good places to look for microfossils.

In summary, the geological evidence for stable liquid water, and the atmospheric models developed to explain this stability, suggest that conditions on Earth and Mars may have been fundamentally similar during the first hundred million years and perhaps for as long as ~10⁹ years or so. Clearly, subsequent planetary evolution led to very different histories for the two planets. 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 CO₂ 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.

Nitrogen on Early Mars

In addition to CO₂ and water, N₂ would have outgassed to contribute to the initial atmosphere [Pollack and Yung, 1980]. Nitrogen is of particular interest because it is a major biological nutrient and it appears to have significantly lower concentrations on contemporary Mars compared to the corresponding concentration on Earth. The pressure of N₂ in the Martian atmosphere is currently 0.2 mbar, which is about 4000 times less than at Earth's surface. As shown in Table 1, estimates for the initial inventory of nitrogen vary considerably, but even the higher estimates are low compared to levels on Earth. The nitrogen cycle on Mars could be a key in considerations of early life on Mars.

Nitrogen in the primitive atmospheres of both Earth and Mars is thought to have been in the form of N₂ [Levine *et al.*, 1982a; Levine, 1985]. Nitrogen in the form of ammonia (NH₃) is considerably more efficient in producing organic compounds in chemical synthesis experiments

than is N₂ [Miller, 1953], and thus it was proposed by origin of life researchers as a component of the early atmosphere of Earth (see, for example, Sagan and Muellen [1972] and Sagan [1977]). However, photochemical modeling studies showed that NH₃ is photochemically unstable on Earth and Mars [Walker, 1977; Kuhn and Atreya, 1979; Kasting, 1982]. In an N₂-CO₂ atmosphere, nitrogen is converted to NO in the high-temperature core of a lightning bolt. Mancinelli and McKay [1988] have recently published theoretical calculations, tied to the experimental work of Levine *et al.* [1982b], for the rate of NO production by lightning in such an atmosphere. They also suggested that any NO produced would become nitrate, a biologically useful form of fixed nitrogen. Their results, which are shown in Figure 4, can be applied to the early atmosphere of Mars. For example, in an atmosphere with 100 mbar N₂ and 1 bar CO₂ (production ~ 10¹⁶ molecules J⁻¹), lightning rates comparable to the rate on the present Earth (~4 × 10¹⁰ W [Borucki and Chameides, 1984]) would require less than 10⁹ years to convert half of the atmospheric nitrogen to nitrate. Thus nitrogen could have been rapidly removed from the atmosphere by two processes, nonthermal escape of N atoms to space [McElroy *et al.*, 1977; Fox and Dalgarno, 1983] and burial deep in the regolith as nitrates (perhaps in conjunction with the burial of CO₂ as carbonates). Eventually, in the absence of sustained geological recycling mechanisms, the atmospheric nitrogen must have diminished to its present low value.

Unfortunately, the Viking XRF mineralogical analysis experiment was not capable of detecting nitrogen in the

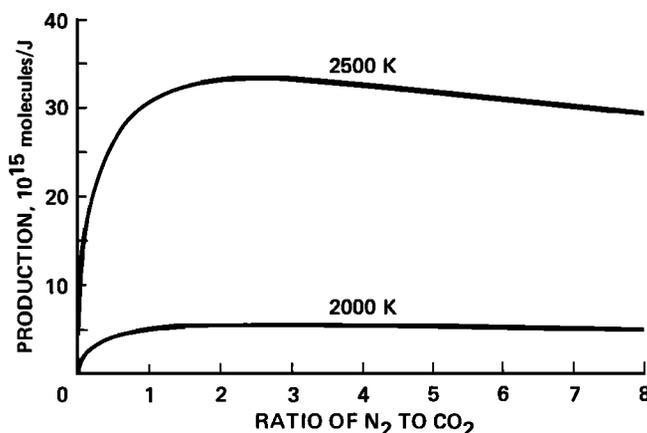


Figure 4. Theoretical calculation of nitrogen fixation in a CO₂-N₂ atmosphere [from Mancinelli and McKay, 1988]. The yield of NO per joule of lightning energy is plotted as a function of the N₂ to CO₂ ratio in the atmosphere. The two curves are the two freeze-out temperatures used in the model calculations. Lightning in an early Martian atmosphere could have formed significant amounts of nitrate. A low initial concentration of nitrogen and subsequent loss of nitrogen to space may have been limiting factors for biology on Mars.

Martian soil [Toulmin *et al.*, 1977], and so there are virtually no data on the existence or form of any soil nitrogen compounds on Mars. Moreover, the Mars Observer orbiter mission planned for 1992 will not be able to add much in this area. This is an important area in which better data are needed to constrain models of the total nitrogen budget and the history of nitrogen on Mars.

As discussed above, nitrogen on early Mars would have been available in two forms: atmospheric N_2 and nitrate. Nitrogen is a key biological element, and the ability to incorporate N_2 into biologically useful forms is the limiting process for many of Earth's ecosystems. Atmospheric nitrogen is not biologically available until it is incorporated into other N compounds (nitrate or ammonia). Bacteria utilize the nitrogenase enzyme to "fix" N_2 into biologically useful forms. Laboratory investigations suggest that the ability of the nitrogenase enzyme to incorporate nitrogen is reduced if the partial pressure of N_2 is below ~100 mbar [Jensen and Cox, 1983], although recent experimental work has shown that nitrogen-fixing organisms can still grow in N concentrations of a few tens of millibars and lower (R. Mancinelli, personal communication, 1988). Thus the availability of nitrogen in the Martian atmosphere may have been more limiting to growth than in terrestrial ecosystems. Along these lines the decrease of atmospheric nitrogen may have played a determining role in the deterioration of the environment that led to the extinction of Martian life.

In addition to biological fixation of atmospheric N_2 , nitrate produced by shock heating of the atmosphere by lightning strokes and meteoritic impact could have been an important biological resource for any early Martian biota as it is believed to have been on early Earth [Mancinelli and McKay, 1988]. If there were nitrogen-utilizing organisms on early Mars, they may have played an important role in cycling any dissolved nitrate back into the atmosphere [Mancinelli and McKay, 1988], allowing escape to space.

The isotopic ratio of nitrogen ($^{15}N/^{14}N$) on Mars is particularly interesting because it is believed that the isotopic ratio of atmospheric nitrogen has varied monotonically with time because of atmospheric escape, enriching the heavier isotope [McElroy *et al.*, 1977; Fox and Dalgarno, 1983]. Hence the N isotopic ratio of organic material or nitrates in the Martian sediments may reflect the time of incorporation. Along similar lines, Banin and Navrot [1979] have suggested that organic carbon and fixed nitrogen are key elements that are enriched by the presence of life above their natural geochemical abundances and may be applicable to the study of Martian sediments. If the C/N ratio of biological material is invariant and if the relative concentrations of C to N varied throughout the history of the Mars atmosphere, then the ratio of C/N in organic material may be a way to differentiate between biological versus abiological origins.

Volcanic Activity on Mars

An ancient, densely cratered terrain covers about two-thirds of the surface of Mars, generally in the southern hemisphere. This terrain bears a superficial resemblance to the densely cratered lunar highlands. The number density of large craters (>30 km) is high but not saturated (see, for example, Carr [1981]). Since the impact history of Mars is believed to have been similar to that for the Moon, this densely cratered terrain must date back to the declining phase of heavy bombardment [Hartmann, 1973; Soderblom *et al.*, 1974], about 3.8 billion years ago, with much reduced impact rates continuing to the present (Figure 5). The presence of valley networks in this ancient terrain suggests that these terrains were formed during a period of warm, moist climatic conditions. The northern portion of the planet is primarily covered by sparsely cratered plains thought to be formed by lava flows which clearly postdate the end of the heavy bombardment.

At present, Mars is seismically and volcanically inactive when compared to the Earth [Greeley and Spudis, 1981; Carr, 1981], although there is ample evidence for tectonic and volcanic activity [Greeley and Spudis, 1981; Head and Solomon, 1981] and increased surface heat flows in the past [Toksöz and Hsui, 1978; Davies and Arvidson, 1981]. Most notable is the Tharsis bulge, a roughly circular feature covering nearly a quarter of the planet's surface with a mean elevation over 11 km above the planetary average [Carr, 1974]. The large shield volcanos, such as Olympus Mons (27 km above the mean datum), are found atop Tharsis (see, for example, Wu *et al.* [1984]). Surrounding Tharsis is a pattern of faults radial to the bulge. As only the oldest surfaces retain the fault pattern, it is believed that the formation of Tharsis occurred early in the planet's history [Wise *et al.*, 1979]. However, the low level of craters on Tharsis indicates that its formation occurred after the heavy bombardment. There is some evidence that volcanic activity has occurred, albeit at a reduced level, for most of Martian history [Greeley and Spudis, 1981; Greeley, 1987]. The general alignment of Valles Marineris canyons, which extend east from the base of Tharsis, and the presence of fault scarps suggest that these canyons were formed by faulting probably related to the formation of Tharsis itself [Head and Solomon, 1981].

The Tharsis event has potential significance to the scenarios of early life, since the volcanic activity may have provided a source of heating to melt snowfall or ground ice and meltwater may have accumulated in the nearby canyon. This is discussed in more detail in the next section.

ECOLOGICAL IMPLICATIONS OF EARLY CLEMENT PERIOD

The theory of the origin of life on early Mars is based on the evidence that conditions on early Earth and early Mars were similar. Figure 5 is a schematic representation,

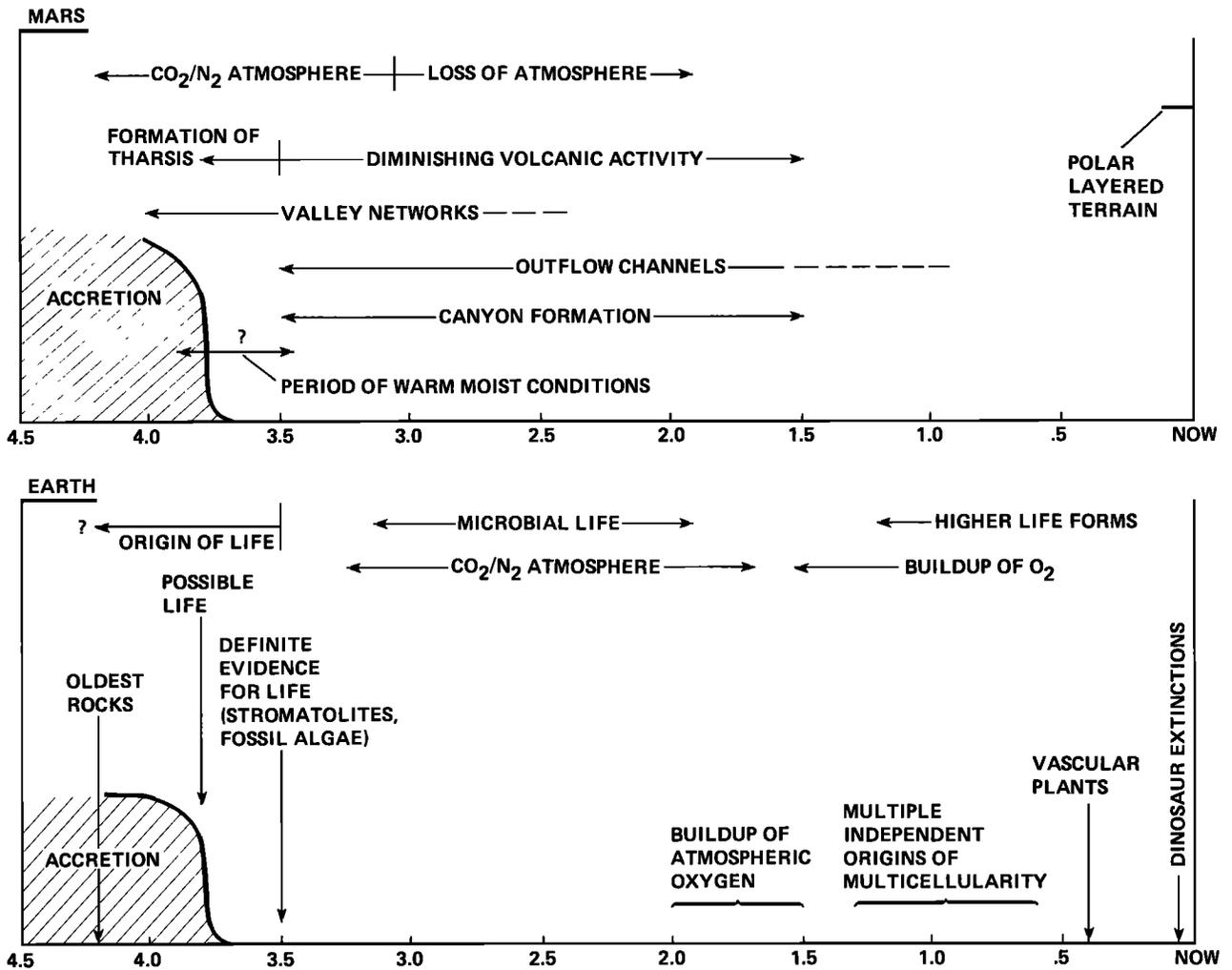


Figure 5. Major events in the history of the Earth (based upon the work of Walker [1977], Schopf [1983], and Holland [1984]) and Mars (based upon the work of Carr [1981] and Pollack et al. [1987]). The period of moist surface conditions on Mars may

have corresponded to the time during which life originated on Earth. The similarities between the two planets at this time raises the possibility of the origin of life on Mars.

adapted from McKay [1986], of the major events in the biogeochemical history of Earth (based on the work of Walker [1977], Schopf [1983], and Holland [1984]) and geological history of Mars (based on the work of Carr [1981]). The formation of the Earth occurred about 4.5 Gyr ago, and the late phase of accretion proceeded through 3.8 Gyr ago (see, for example, Holland [1984]). The Earth's crust was probably cool enough to support stable liquid water by 4.0 Gyr ago, although some late impactors may have episodically heated the Earth's entire surface to above the boiling point of liquid water, thereby resetting the biological clock [Maher and Stevenson, 1988]. Life appears to have been widespread on the Earth and existed in sophisticated ecological communities by 3.5 Gyr ago [Schopf, 1983; Schopf and Packer, 1987]. Schopf and Packer [1987] have suggested that oxygenic photosynthesis by cyanobacteria existed at this time. It is possible that the organic material recovered from the 3.8-Gyr-old

Isua sediments are also indicative of biological activity (see, for example, Robbins [1987] and Schidrowski [1988]) [cf. Schopf, 1983], suggesting an even earlier origin for life. Thus the time interval for the origin of life on Earth is between approximately 4.0 and 3.5 Gyr ago, and life may have evolved over a much shorter time period.

On Mars it appears that there was liquid water on the surface at the termination of the late bombardment, some 3.8 billion years ago, and therefore there must have been a warm atmosphere of approximately 1 bar CO₂. During this time, and after, there was extensive crustal and volcanic activity. Habitats suitable for the origin and survival of life may have existed for hundreds of millions up to a billion years.

The similarities between the initial environments of Earth and Mars are compared in Table 2. This table reflects the biologically important aspects of a planetary habitat. The period of most interest is between 4.5 and 3.5

TABLE 2. Comparison of Early Earth and Early Mars

Property	Early Earth	Early Mars
Water	oceans	evidence for surface liquid water; hydrological cycle(?)
Temperature	>273 K	≈ 273 K
Atmosphere	CO ₂ , N ₂ , H ₂ O: > 1 atm	CO ₂ , N ₂ (?), H ₂ O: ≈ 1 atm
Volcanic and geothermal activity	yes	yes
Geochemical carbon cycle		
CO ₂ → carbonate rocks	reactions in water	reactions in water
Carbonate rocks → CO ₂	subduction and volcanism	early volcanism only
Duration of dense atmosphere	4.5 Gyr to present	4.5 Gyr to 3.5 Gyr(?)
Preservation of rock record	highly altered and reworked	~ two thirds of the surface is older than 3.8 Gyr
Biology	diverse life by 3.5 Gyr	unknown

Adapted from McKay [1986].

Gyr ago. During this time, life arose on Earth and reached a fair degree of biological sophistication. The emerging picture of early Mars and its similarity to early Earth has generated many opportunities to tie the geophysical understanding of Mars to biological processes. In the following subsections we review some of the more interesting areas in exobiology that have strong ties to the geophysical understanding of Mars.

Comparison to Earth's Earliest Biosphere

In considering the question of life on early Mars, we have developed a line of reasoning about Martian life that is based upon the assumption that in the early stages of microbial development, life on another Earthlike planet would follow a similar pattern of evolution to that on Earth. This assumption may be overly geocentric but represents a conservative approach to speculating about life on early Mars. The extent to which this generalization is valid is unknown, since we have studied only one example of a planet-life relationship: Earth. General ecological attributes such as uptake of carbon dioxide via photosynthesis (CO₂ being the obvious C source and sunlight being the obvious energy source) and incorporation of the essential macronutrients, such as P and N, are on comparatively firm ground. Of much less certainty is the universal nature of the biochemical machinery by which Earth's organisms carry out these ecological processes. Specific enzymes that are essential and ubiquitous on Earth such as carboxalase (for incorporating CO₂ into reduced organic carbon compounds) and nitrogenase (for fixation of N₂) could conceivably have completely different structures in life that evolved on a planet other than, but similar to, Earth. Almost certainly, the details of evolution beyond the microbial level are very much dependent on the specific historical details of the environment, and the evolutionary process and generalizations are extremely fragile. However, this complex period

of path-dependent evolution did not occur on Earth until at least 1 Gyr ago. It is doubtful that Mars ever achieved the conditions (such as high O₂ concentrations) that seemed to be the harbingers of the explosive growth in biological complexity at the start of the Phanerozoic.

An interesting, and practical, example of extrapolation from Earth's ecosystems to those that may have existed on early Mars is that of stromatolites, which are defined by *Awramik et al.* [1976] as organosedimentary structures produced by sediment trapping, binding, and/or precipitation as a result of the growth and metabolism of microorganisms. Stromatolites are one of the primary forms of fossil evidence for microbial life on Earth during the Precambrian. Their formation is typically associated with the phototactic (i.e., light-seeking) properties of cyanobacteria and algae (see, for example, *Golubic* [1973,1976]). It is reasonable to suppose that if life arose on Mars, the shallow-water habitats would have been populated by algaelike photoautotrophs. Certainly, it would appear that CO₂ was available on early Mars as a source of C atoms to any photoautotrophic organisms that may have existed to consume it. As occurs on Earth, the requirement for light would have driven these algaelike organisms to move above any sediment that gradually deposited upon them. In the absence of other organisms grazing on them (a problem for the terrestrial stromatolites which did not evolve until the Phanerozoic) this basic mechanism of phototaxis would result in the formation of stromatolites. 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. 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 the motion toward light, through obscuring sediments, would have a selective advantage for those organisms that utilize it. Thus we assume that

Darwinian evolution would equally apply to life on Mars as it has to life on Earth.

Tharsis and the Valles Marineris as Sites for Early Life

The Tharsis plateau and the associated canyons are sites of special interest to exobiological investigations of Mars. As mentioned before, the lack of impact features suggests that Tharsis formed after the end of the early bombardment, but the pattern of faults associated with the formation of Tharsis suggests that it occurred early in Martian history. Carr [1981] placed the formation of Tharsis at between 3.8 and 3.5 Gyr ago (see Figure 5) and the formation of the circum-Tharsis fractures at 3.5–2.9 Gyr ago.

Associated with the formation of Tharsis was the formation of the Valles Marineris canyon system. The floors of many of the canyons contain deposits of horizontally layered material where individual layers are laterally continuous over tens of kilometers (Figure 6). It has been suggested that these deposits were laid down in lakes that

existed in these canyons early in Martian history [e.g., McCauley, 1978; Lucchitta, 1981; Lucchitta and Ferguson, 1983; Nedell *et al.*, 1987]. Nedell *et al.* [1987] conducted a detailed study of the Valles Marineris layered deposits using Viking high-resolution images. They considered and discarded several alternative hypotheses for the origin of the layered deposits, including aeolian deposition, erosional isolation of canyon wall material, and subaerial explosive volcanism. Their conclusion was that deposition in standing water was the only mechanism that could readily explain the distribution, lateral continuity, horizontality, great thickness, and rhythmic nature of the deposits.

Carr [1986] has suggested that liquification of local rocks mixed with a high proportion of clays could have formed the thick stacks of seemingly water-lain, easily erodible deposits within these canyons. Alternatively, McKay and Nedell [1988] have suggested that a considerable fraction of the possible Martian paleolake sediment could be carbonate material that was precipitated in



Figure 6. Viking orbiter image of Hebes Chasma (0°S, 75°W). This canyon is a box canyon about 280 km long. The mesa in the center of the canyon shows layered deposits that are believed to have been deposited in standing bodies of water [Nedell *et al.*, 1987]. The lakes that may have existed in these canyons may

actually date to the period after the initial warm epoch that formed the dendritic channels (Figure 2) and thus are of interest exobiologically as a possible habitat for life after ambient conditions on Mars had become inimical to life.

standing water under conditions of high atmospheric pressures of CO₂. This suggestion is consistent with the evolutionary scenarios proposed for the Martian atmosphere discussed above.

It may be argued that the Tharsis and Valles Marineris events postdate the valley networks and the period of dense, moist atmospheric conditions on Mars. While this may be true, it does not diminish their significance in terms of possible habitats for life. In fact, the occurrence of local geothermal activity and the presence of liquid water are, by themselves, an indication that conditions were suitable for life. Microbial life can readily adapt to high temperatures, and in fact, there is growing evidence that the common ancestor of all organisms on Earth was a sulfur-metabolizing thermophile [Woese, 1987; Lake, 1988]. Microbial assemblages associated with geothermal locales have been widely reported (see, for example, Brock [1978]). As our understanding of volcanic processes on Mars grows, the range of biological possibilities may grow as well. Depending on the duration of the Tharsis activity and the timing of the water flows, the Valley Marineris, by itself, could have been a suitable site for the origin of life on Mars. If these events occurred shortly after the late bombardment, at a time when the Martian atmosphere was thinning and surface temperature was dropping, the lakes in the Valles Marineris could have been the last major habitat for a dwindling Martian biota [McKay, 1986; McKay and Nedell, 1988]. There is even the intriguing possibility that volcanism may have occurred in the Valles Marineris in geologically recent times [Lucchitta, 1987].

Ice-Covered Lakes as Habitats on Early Mars

One interesting possibility that has grown out of recent work in the dry valleys of Antarctica is that the period on Mars during which biologically favorable habitats could persist may have been greatly extended by the phenomenon of perpetually ice-covered lakes [McKay *et al.*, 1985; Wharton *et al.*, 1987; McKay and Nedell, 1988]. Although the mean temperature of the so-called Antarctic "dry valleys" is 20°C below freezing, deep lakes (>30 m) are formed by groundwater flow and by transitory melting of glacial ice [Parker *et al.*, 1982].

Using data from perpetually frozen Antarctic lakes, McKay *et al.* [1985] developed a general energy balance model for determining the thickness of ice on these lakes. If the lake is large, lateral conduction of heat from the shore is negligible. In addition to sunlight penetrating the ice, heat is added to the lake by geothermal heat flow (usually small) from the bottom and by the influx of meltwater whose latent heat is released at the ice-water interface when it freezes to form new ice. Only a small amount of heat is brought in to the lakes by the inflowing water, since its temperature is close to freezing. Conduction of heat through the ice is the only means of heat

exchange between the liquid water and the surface; hence in steady state the rate of supply below any level in the ice must equal the conduction of heat upward in the ice at that level. This constraint determines the temperature lapse rate in the ice cover [McKay *et al.*, 1985], while the mean surface temperature and the freezing temperature of the ice-water interface determine the thickness of the ice. McKay *et al.* [1985] applied this model to the Antarctic dry valley lakes and also showed that any groundwater-fed lakes on the present Mars would have ice cover thicknesses between 65 and 650 m.

McKay and Nedell [1988] have also applied this model to Martian paleolakes and have determined that for reasonable assumptions of meteorological conditions, the ice thickness would have been 3.4 m if the mean temperature was 250 K and 11 m and 19 m for mean temperatures of 240 K and 230 K, respectively. For comparison, the ice cover thickness on current Antarctic lakes is 4–6 m. For the same surface temperature, Mars lakes would have thinner ice covers than Antarctic lakes because of the fact that the mean insulation on the primordial equatorial Mars, even with the faint young Sun and dust attenuation, was greater than in Antarctica today [McKay and Nedell, 1988].

A further aspect of the perennially ice-covered lakes in the Antarctic is the enhanced level of atmospheric gases. The water in these lakes contains dissolved atmospheric gases at concentrations greatly in excess of the value that would be in equilibrium with the atmosphere. This results from the inflow of meltwater that has been aerated on the surface. This meltwater carries atmospheric gases (O₂, N₂, etc.) in solution into the lakes. The gases are then concentrated when the water freezes at the bottom of the ice cover. For example, Lake Hoare in Taylor Valley, Antarctica, has ~250% of the O₂ and ~150% of the N₂ that would be at equilibrium with the atmosphere [Wharton *et al.*, 1986, 1987]. The O₂ supersaturation is higher because of a biological net source [Wharton *et al.*, 1987].

The physical processes that characterize an ice-covered lake are shown schematically in Figure 7. In addition to providing a liquid water environment held at 0°C that may have significantly extended the biological "window of opportunity" on Mars, the gas concentration mechanisms that operate in ice-covered lakes would have affected the gas budget of the lake, enhancing atmospheric gases. This could have been a vital source of biologically important gases (principally CO₂ and N₂) as the Martian atmosphere thinned.

The ice-covered lake habitat is of major biological significance in the inhospitable dry valleys of Antarctica. A mat of microbial organisms composed primarily of the cyanobacteria *Phormidium frigidum* Fritsch and *Lyngbya martensiana* Menegh, several species of pennate diatoms, and heterotrophic bacteria occur abundantly throughout

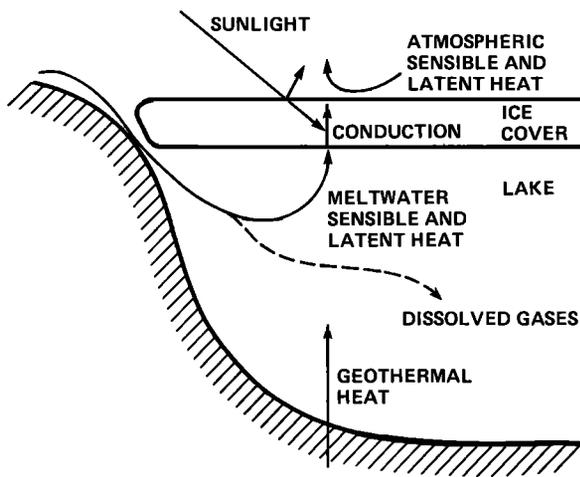


Figure 7. Schematic of the physics of an ice-covered lake showing the buffering of temperature and the concentration of atmospheric gas that occur in a perpetually ice-covered lake. Such lakes are found in the dry valleys of Antarctica and may have been important habitats on Mars as the atmosphere thinned and the surface cooled.

much of the benthic regions of these lakes [Wharton *et al.*, 1983]. These microbial mats are precipitating calcite and trapping and binding sediments, thereby forming alternating laminae of organic and inorganic matter. The unique feature of many of these benthic mats is their development into modern, cold-water stromatolites [Parker *et al.*, 1981; Love *et al.*, 1983; Wharton *et al.*, 1982].

The carbon isotopic composition of carbonate and reduced carbon in microbial mats and biogenic sediments is often preserved during their transformation into stromatolites [Barghoorn *et al.*, 1977; Estep, 1984; Schidlowski, 1988]. By studying the Antarctic lakes and understanding the exact nature of the sedimentary record in the lake bottom, it may be possible to develop a set of techniques for the *in situ* analysis of the sediments from any paleolakes on Mars and provide a data base for reconstructing the nature of the Martian lake environment and the life-forms, if any, that lived there.

In addition to the Valles Marineris lake features, there are many sedimentary features that date back to the potentially biologically active period of Martian history. Goldspiel and Squyres [1989] have recently suggested that there are playalike lake basins in the ancient terrain in the Margarifer Sinus region. This is an ancient region of Mars laced with many channels [Baker, 1982]. Sediments in these regions are of particular interest, since they may provide the oldest record of water activity on Mars.

COULD LIFE HAVE SURVIVED TO THE PRESENT?

Three key questions must be addressed when considering whether or not life could have survived on Mars to the present epoch. They are as follows: (1) To what extent can

organisms adapt to long periods without liquid water? (2) How did the Martian climate evolve from an early warm period to the present state? (3) Could suitable habitats have existed throughout Martian history in which life could survive and occasionally grow? The critical consideration in this regard is the availability of liquid water, both throughout Martian history and during the present epoch.

Although early Mars may have been warm and wet compared to the current conditions, it was probably much cooler and dryer than early Earth because of its greater distance from the Sun and its initially lower volatile inventory. Throughout its history the Martian climate undoubtedly experienced larger temperature fluctuations than were experienced on Earth. And, although the climate may have remained warm enough to globally support liquid water for as much as 10^9 years [Pollack *et al.*, 1987], as conditions gradually got colder, the evolutionary pressure to adapt to colder environments would have been intense.

On Earth, life does not grow at low water activities (the partial pressure of water vapor over a solution divided by its partial pressure over pure liquid water). Most bacteria require a water activity of 95%, extreme halophiles can tolerate 75%, and only certain eukaryotes can survive down to 60% [Mazur, 1980; Kushner, 1981]. On a warm, water-rich planet like Earth, there may have been little selective pressure to adapt to very cold environments or to metabolize without liquid water. However, the fact that on Earth the vast expanse of the polar plateau is barren of life, except at the periphery where liquid water is found, suggests that it may not be biologically possible for Earthlike life to grow without water in the liquid state. Survival is another issue, and many terrestrial organisms are able to survive years of dehydration and/or subfreezing temperatures [Mazur, 1980; Crowe and Crowe, 1989; Crowe and Clegg, 1978].

Since Mars is not covered with an active biota, it seems probable that if there was life during an earlier period, it is now extinct. If, somehow, life has survived to the present, then on the basis of the same observation one can conclude that it has not fully adapted to current conditions on Mars and exists only in restricted habitats or dormant forms. The most likely restriction is the scarcity of liquid water, and thus life, if it has survived, is probably confined to regions where at least transient pockets of liquid water may occur. Such life would need the capability to remain dormant for extremely long periods of time until favorable conditions for metabolism occurred.

Climatic Evolution and Associated Time Scales

As discussed above, the primary factor responsible for the deterioration of Martian climate and the progressive cooling of the planet is thought to have been the formation of carbonate rocks and gradual loss of the atmosphere. Since the absence of open bodies of liquid water would

have greatly retarded the loss of a dense CO₂ atmosphere [Kahn, 1985; Pollack *et al.*, 1987], the rate of temperature drop on the Martian surface may have been greatly reduced once the mean annual temperature fell below freezing. Hence it is likely that Mars' climatic history was characterized by two distinct periods. The first period would have been characterized by rapid formation of carbonates (and concomitant loss of CO₂) driven by an active hydrological cycle and the presence of standing bodies of water. This period would have been followed by a much more gradual loss of CO₂ as any standing water developed perennial ice covers and the hydrological cycle became seasonal only or was entirely removed, leaving only groundwater flow as a source of liquid water [McKay and Nedell, 1988]. Thus the climate of Mars may have deteriorated to its present state rather gradually compared to time scales associated with biological adaptation to changing conditions.

In addition to the gradual cooling of the Martian climate, periodic climatic variations may have influenced the continued survival of life on Mars. Of interest in this regard is the magnitude of climatic variations that occur on Mars today and in the past [Carr, 1982; Pollack and Toon, 1982]. The current Martian climate experiences substantial temperature and possibly pressure changes caused by alterations in the distribution and intensity of sunlight due to periodic variations of Mars' orbital parameters [Ward, 1974; Ward *et al.*, 1979; Pollack and Toon, 1982]. These variations may have been even larger on early Mars, although their climate effects may have been subdued as long as there was substantial greenhouse warming and polar cap temperatures remained high enough to prevent the formation of seasonal CO₂ polar caps.

Variations in the obliquity exert the strongest influence on Martian climate [Ward *et al.*, 1974]. The obliquity of Mars is now 25.1° and oscillates periodically by about ±13° with a dominant periodicity of ~10⁵ years and a modulation period of ~10⁶ years [Ward, 1974; Ward *et al.*, 1979]. Currently, the Martian obliquity is forced by torques near a resonant condition, and prior to the formation of Tharsis the average Martian obliquity may have been closer to 32° with a maximum of 46° [Toon *et al.*, 1980]. During periods of high obliquity the polar caps receive more solar insolation than at present, which results in higher summertime temperatures at the poles. The large variations of insolation may have impacted climate on early Mars before the formation of Tharsis [Ward *et al.*, 1979]. Toon *et al.* [1980] show that even without the greenhouse effect provided by a dense CO₂ atmosphere, daily average summer temperatures at high latitudes would significantly exceed the freezing point of water when the obliquity is 45°.

On present Mars, orbital variations may still produce substantial variations in Martian climate. If a large reservoir of CO₂ were present in the polar caps of Mars,

the increase of insolation at the polar regions during high-obliquity periods would result in the atmospheric pressure increasing to as high as 40 mbar [Ward *et al.*, 1974; Toon *et al.*, 1980]. However, the Viking results indicate that the polar caps contain only a limited reservoir of CO₂ [Fanale *et al.*, 1982]. Even though the polar caps apparently do not buffer atmospheric pressure, the regolith probably does have this capability [Davis, 1969; Fanale and Cannon, 1974, 1979; Zent *et al.*, 1987]. The Martian surface may be covered by a thick regolith in absorption equilibrium with the atmosphere. The ability of this regolith to absorb CO₂ is a function of both pressure and temperature, with more CO₂ being absorbed at lower temperatures. As temperatures increase toward the poles and decrease toward the equator, CO₂ will be desorbed in the polar regions and adsorbed at low latitudes. Depending on the absorption properties of the regolith, at high obliquity the atmospheric pressure could increase by as much as several tens of millibars above present values [Toon *et al.*, 1980; Fanale *et al.*, 1982]. During these periods, summer polar ground temperatures as high as 273 K may occur, and melting is possible in the water ice cap [Toon *et al.*, 1980].

During low-obliquity periods the poles would be cold enough for CO₂ to remain stable throughout the year and pressure to fall below 1 mbar. At these low pressures the regolith would nearly completely desorb, and all the CO₂ in the atmosphere-regolith-cap system will reside in the cap [Fanale *et al.*, 1982]. Dust storm activity would cease at such low pressures, thereby increasing the albedo of the cap ice and causing further cooling. The global average temperatures would not be significantly colder during low obliquity because the CO₂ greenhouse amounts to only a few degrees Kelvin at present [Pollack, 1979]. However, even transient liquid water at the surface would be virtually impossible at such low atmospheric pressures [Kahn, 1985], as shown in Figure 8. A significant amount of ice may also be exchanged between the regolith, the atmosphere, and the polar cap as the obliquity changes [Fanale *et al.*, 1982, 1986].

In addition to the above theoretical arguments for periodic climate change on Mars, there is some geomorphological evidence that liquid water occurred episodically over geologic time scales [e.g., Soderblom and Wenner, 1978] (also see reviews by Rossbacher and Judson [1981], Squyres [1984], and Carr [1987]). Masursky *et al.* [1987] presented evidence for some very recent channel formation. However, there is considerable debate about the nature of the heating source responsible for the formation of these channels. Geological proof for episodes of liquid water activity throughout Martian history, whether associated with geothermal activity or with climatic warming, would have important implications for the possible survival of life on Mars to the present time.

The large variations of climate on Mars, caused by

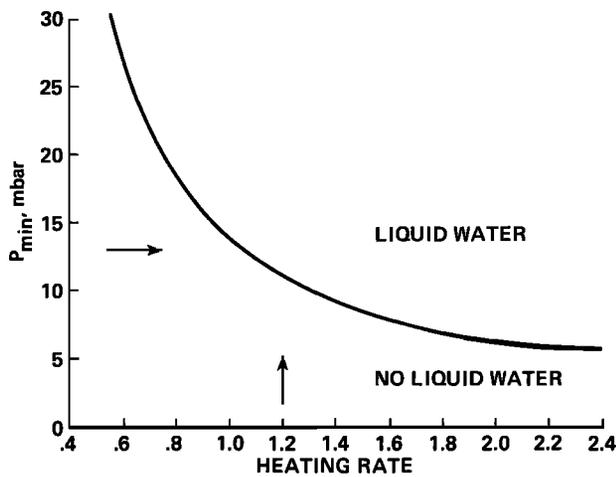


Figure 8. Minimal atmospheric pressure required to support liquid water from melting ice as a function of the heating rate of the ice surface in units of the present average solar insolation on Mars (adapted from Kahn [1985]). Arrows indicate the maximum range of each of these parameters on the present Mars. Thus liquid water is difficult, but not impossible, to form under present conditions.

orbital forcing on 10^5 - and 10^6 -year time scales, relatively short periods compared to evolutionary time scales, may have provided additional stress on life as well as possibly a selective pressure for developing strategies for survival during long periods of colder climatic conditions.

Possible Niches for Life on Mars

Liquid water is the sine qua non for life as we know it. In order to evaluate the possibility that life may have survived to the present we need to examine the locations where liquid water is physically possible. Below we evaluate some possible niches where liquid water may occur and discuss their likelihood as refuges for life. Three primary niches are identified: (1) transient sources of near-surface liquid water, (2) meltwater within a dusty snowpack, and (3) subsurface reservoirs of meltwater deep within the regolith or at the base of the polar caps.

Strictly speaking, transient pockets of liquid water on the surface are not impossible, although the evaporation rates for liquid water in contact with the atmosphere are very high [Kahn, 1985]. Figure 8 shows the relationship between the atmospheric pressure and the heating rate required to produce stable liquid water on Mars. Basically, ice can melt to form liquid water only if the rate at which water molecules are released from the ice can exceed the rate at which they are carried away by evaporation. The arrows indicate the extremes of pressure and solar insolation in the present Mars. With the present climate, special conditions are required before even transient liquid water can form. These conditions include high heating rate, low altitude (for high pressure), and a reduced

evaporation rate. Saturated salt solutions, by depressing the vapor pressure of water, would allow the liquid state to occur more readily (see, for example, Zent and Fanale [1986]). The Viking landers discovered high concentrations of salts in Martian soil [Clark, 1978].

One example of a surface environment where conditions could allow the formation of liquid water is the pore spaces of rocks. Water reaches saturation in the Martian atmosphere at typical nighttime temperatures. When saturation is exceeded, water frost may be deposited on surface rocks and soil. Such deposits were seen by the Viking lander cameras during autumn [Hart and Jakosky, 1986]. Under favorable conditions, transitory moisture could form from the melting of this frost, and some of it could soak into the pore spaces in rocks and exist there for longer periods than would be possible in open contact with the atmosphere. Liquid could persist for even longer periods as a brine solution. An Earth analog to this type of niche is found in the sandstone rocks in the dry valleys of Antarctica [Friedmann and Ocampo, 1972; Friedmann, 1982, 1986] and in hot deserts [Friedmann, 1980], where cryptoendolithic lichens grow in subsurface pore spaces. Water is retained by these rocks despite low ambient relative humidities [Friedmann et al., 1987].

For life on Mars to take advantage of such a niche, organisms would need to be able to remain dormant for long periods of time and then quickly and efficiently metabolize when temperature and water conditions allowed growth. This is essentially the metabolic pattern accomplished by the cryptoendolithic lichens on Earth [Friedmann et al., 1987], albeit to a much lesser extent than would be required on Mars.

The possibility of fairly stable brine solutions at or just below the Martian surface has been suggested [Zisk and Mouginiis-Mark, 1980] as a possible explanation of strong Earth-based radar reflectivities that are seasonally variable near Solis Lacus and Noachis-Hellespontus. These same areas were suggested by Huguenin et al. [1979] to be possible sites of near-surface water activity. However, the existence of near-subsurface water is controversial (A. P. Zent et al., Possible Martian brines: Radar observations and models, submitted to *Journal of Geophysical Research*, 1989), and alternative explanations for the radar observations are possible [Zisk and Mouginiis-Mark, 1980].

The stability of near-surface brine solutions has been discussed by Zent and Fanale [1986], who concluded that certain brines may exist for periods of 10^7 years under current conditions. This is a time scale comparable to orbital forcing of the Martian climate.

The polar regions represent another location where liquid water may occasionally be possible at the surface. Clow [1987] has shown that meltwater is possible in a dusty Martian snowpack such as the residual water-ice

polar cap. With optimal dust loading, melting can occur in the upper few centimeters of dense, coarse-grained snow at atmospheric pressures as low as 7 mbar [Clow, 1987]. At these depths, sufficient sunlight penetrates the ice to support photosynthesis. A surface ice crust could provide the needed inhibition against evaporation. There are organisms on Earth that grow under the surface of water-saturated snow (the snow algae) [Hoham, 1975; Hoham et al., 1983] and in small melt holes, known as cryoconite holes, on glaciers [Wharton et al., 1981, 1985].

Another location where liquid water has been suggested to occur is deep below the base of the north polar cap on Mars. As discussed by Squyres and Carr [1986], 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 [Clifford and Hillel, 1983]. Figure 9 shows a cross-section of the Martian crust and the implied distribution of permafrost, i.e., those regions on Mars that are permanently below the frost point. In other regions the temperatures are seasonally high enough that water ice, in contact with the atmosphere, would have evaporated over geologic time, leaving the ground dehydrated. Water that sublimated out of these areas would have been deposited at high latitudes or in the polar caps. Clifford [1987] (see also Fanale [1976]) has pointed out that the deposition and retention of ice at the polar surface results in a situation in which the equilibrium depth to the melting isotherm has been exceeded, causing ice to melt at the base of the cryosphere. Water that results from this basal melting would fill the available pore space that exists beneath the frozen outer

crust. Since a porous regolith may reach to depths of 10 km [Clifford, 1987], the total pore volume in the deep regolith is sufficient to store a quantity of water equal to a layer 1.5 km deep distributed over the Martian surface. Clifford [1987] calculated that the thickness of the north polar cap (4–6 km) is consistent with basal melting maintaining its equilibrium depth. However, the inferred thickness of the south polar cap is 1–2 km, which is smaller than the estimated equilibrium thickness. Thus basal melting may occur in the north polar cap but is unlikely in the south polar cap.

The existence of a meltwater lake at the base of the cryosphere offers another possible location where organisms could survive, although some form of metabolic energy source would be needed since sunlight would be absent. The closest analogy on Earth may be the organisms living in hydrothermal vents obtaining energy by the oxidation of sulfur compounds [Karl et al., 1980]. The Martian surface is 3% sulfur by weight, most probably in the form of sulfate [Toulmin et al., 1977]. Clark [1979] has proposed an energy cycle for a subsurface Martian biota based on sulfur-driven metabolism, requiring a source of H_2 or organic material. He notes that the bacterium *Desulfovibrio* is an anaerobic bacterium that derives energy by catalyzing the reduction of sulfate compounds. This organism appears to be ubiquitous in the soils of Earth, even being found in extreme environments in the Antarctic [see Clark, 1979, and references therein]. Sulfate minerals could be transported to the basal melt layer in the polar cap as a component of the dust which is annually deposited on the polar caps. Thus a plausible energy source exists to power a subsurface Martian biota.

Even though polar basal meltwater could conceivably provide a growth habitat for life on Mars, it is unlikely to be a location where we will have the capability to search for extant life in the near future.

In summary, environments may exist on Mars where

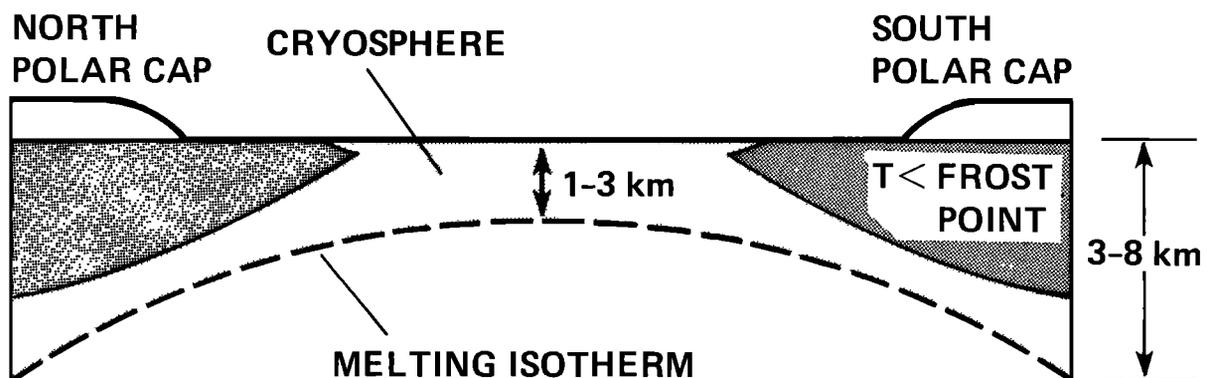


Figure 9. Stability diagram of ground ice on present Mars as a function of latitude. The heavily stippled region shows those areas around the polar caps for which the temperature is below the frost point ($T \sim 200$ K) and ice can exist in equilibrium.

Outside these polar regions, ground ice can exist only if it is isolated from the atmosphere by a diffusive barrier. The melting isotherm is also shown. Liquid water could exist below these depths.

liquid water occurs at least occasionally. One can postulate that organisms have adapted to these environments and still survive on Mars at the present time. However, we emphasize that even in such "oases," conditions are exceedingly hostile compared to conditions in analogous environments on Earth. Further geophysical exploration of Mars is needed to evaluate whether such oases actually exist.

Viking Biology Experiments and Implications for Survival

One primary focus of the Viking mission to Mars was to search for evidence of living organisms. In addition to the lander cameras, which would have shown the presence of any obvious macroscopic life-forms, the Viking landers contained three experiments specifically designed to search for indications of life on Mars: (1) the Gas Exchange Experiment [Oyama and Berdahl, 1977], designed to determine if Martian life could metabolize and exchange gaseous products in the presence of a nutrient solution; (2) the Labeled Release Experiment [Levin and Straat, 1977], which sought to detect life by the release of radioactively labeled carbon initially incorporated into organic compounds in a nutrient solution; and (3) the Pyrolytic Release Experiment [Horowitz and Hobby, 1977], based on the assumption that Martian life would have the capability to incorporate radioactively labeled carbon dioxide in the presence of sunlight (photosynthesis).

The results of these experiments showed that Martian soil exhibited activity which was similar in many ways to the metabolic activity they were designed to detect. However, in detail the results were inconsistent with a biological explanation [Horowitz, 1977; Klein, 1978; Mazur *et al.*, 1978], and a chemical explanation, based upon the presence of a strong oxidant in the soil, has been suggested [Klein, 1979; Ballou *et al.*, 1978; Oyama and Berdahl, 1979]. In addition, the negative results of the Viking gas chromatograph/mass spectrometer (GCMS) search for organic compounds place severe restrictions on the probability of life on Mars. The GCMS failed to detect organic material at levels less than parts per billion for heavy organics and parts per million for lighter ones [Biemann *et al.*, 1977]. The experimental procedure and results of the Viking biology experiments have been reviewed extensively elsewhere [Horowitz, 1977, 1986; Klein, 1978, 1979].

The inferred existence of oxidants in the Martian soil poses an additional challenge to the possibility that Martian organisms survive to the present. The fact that the abundance of organic compounds on Mars was lower than would be expected from the influx of meteorites containing organic material suggests that these oxidants are actively decomposing organic compounds on Mars [Pang *et al.*,

1982]. Any Martian organism with a habitat in this oxidizing layer would likewise be subject to such an attack. Biomass production would be required to keep pace with loss due to this oxidation process. However, as discussed above, biomass production would be severely limited by the restricted occasions when conditions would be conducive to growth.

The details of the mechanism that creates the oxidizing conditions are not well understood, and various mechanisms have been proposed that would explain the production of several different types of oxidants on Mars. The most plausible model is that the solar ultraviolet light acting on the small amount of water in the atmosphere creates hydrogen peroxide in the soil [Hunten, 1979; Oró and Holzer, 1979]. Other suggested oxidants include metallic superoxides created by cosmic rays and triboelectric discharges interacting with Martian minerals [Oyama and Berdahl, 1979] and metallic oxides and/or clay activity [Banin and Margulies, 1983; Banin, 1986] (see also discussions by Huguenin *et al.* [1979] and Pang *et al.* [1982]). Since there is little evidence for extensive reworking of the ancient terrain after 3.8 Gyr [Carr, 1981], this oxidizing material is probably limited to the diffusion depth of the oxidizing agent over its production time. This is highly uncertain, but diffusion may be limited to a depth of a few meters or so by the presence of ground ice [Chyba *et al.*, 1988]. Organic material may be preserved below this depth. It is important to better understand the production mechanisms for oxidants and their possible distribution in order to design better strategies to search for organic remains of past life, as well as extant life, on Mars.

IMPLICATIONS OF FINDING EVIDENCE OF LIFE ON MARS

Clearly, the most important thing that the discovery of life on Mars, even past life, will tell is that the origin of life is a common event, probably happening on most planets with liquid water at the surface. By implication, the universe would be full of life. In addition, Mars may very well contain the deepest and best preserved record of the events that transpired on the early terrestrial planets during the procreative stages, that time during which life might have evolved. On Earth, and probably on Venus as well, the record of this early period has been largely destroyed, and the small samples that are left are usually highly altered. On Mars the cold, the absence of tectonic activity, and the absence of oxygen could have all helped to preserve the record of the steps leading to the origin of life.

Investigating the record of prebiotic and biotic evolution on Mars will involve searching for many things, including [McKay, 1986] direct traces of life such as microfossils,

organically preserved cellular material, altered organic material, morphological microstructures (see, for example, *Campbell* [1982]) and chemical discontinuities associated with life (see, for example, *Friedman* [1986]), isotopic signatures due to biochemical reactions, inorganic mineral deposits attributable to biomineralization (see, for example, *Nealson* [1982] and *Tebo and Emerson* [1986]), and hydrated minerals such as clays as well as water-formed minerals such as carbonates. A useful example is illustrated in Figure 10. 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 [*Lorimer*, 1981; *O'Leary*, 1981; *Estep et al.*, 1978; *Estep*, 1984]. In studies of Earth's earliest biosphere this isotopic shift provides a useful test for determining if organic matter is of biological origin [*Calder and Parker*, 1973; *DesMarais et al.*, 1981; *Schidlowski et al.*, 1983; *Schidlowski*, 1988]. In fact, *Schidlowski* [1988] argues that the presence of the characteristic isotopic shift due to biological activity seen in the Isua metasediments (Figure 10) is presumptive proof of biological origin. It is possible that similar effects may be present on Mars.

Information From a Martian Fossil Record

The discovery that life did originate on Mars would not only be of broad interest, it could also provide insight into many scientific questions concerning life on Earth [*McKay*, 1986]. Certainly, if life evolved on Mars, it would have differences and similarities to life on Earth. Most likely, any early Martian life would have had to respond to the same ecological constraints that early life on Earth did. For example, whether the first organisms on Earth were heterotrophic (consume organic material) or autotrophic (produce organic material via photosynthesis or chemosynthesis) probably depended more on the prevalence of abiologically produced organic material in the environment than it did on the details of the biochemistry of the first organism [*Stoker et al.*, 1989]. The same was probably true for Mars. On Earth we do not have the fossil record required to determine the environmental context in which the earliest organisms lived. Our first record of life is already a mature system (see, for example, *Awramik* [1981] and *Schopf* [1983]). If life evolved on Mars, the record of its early history may be more accessible. Using isotopic and geochemical means [see *Schopf*, 1983] to explore the fossil record on Mars has the potential to shed light on theories of the energy generation mechanism of early life (autotrophy versus heterotrophy).

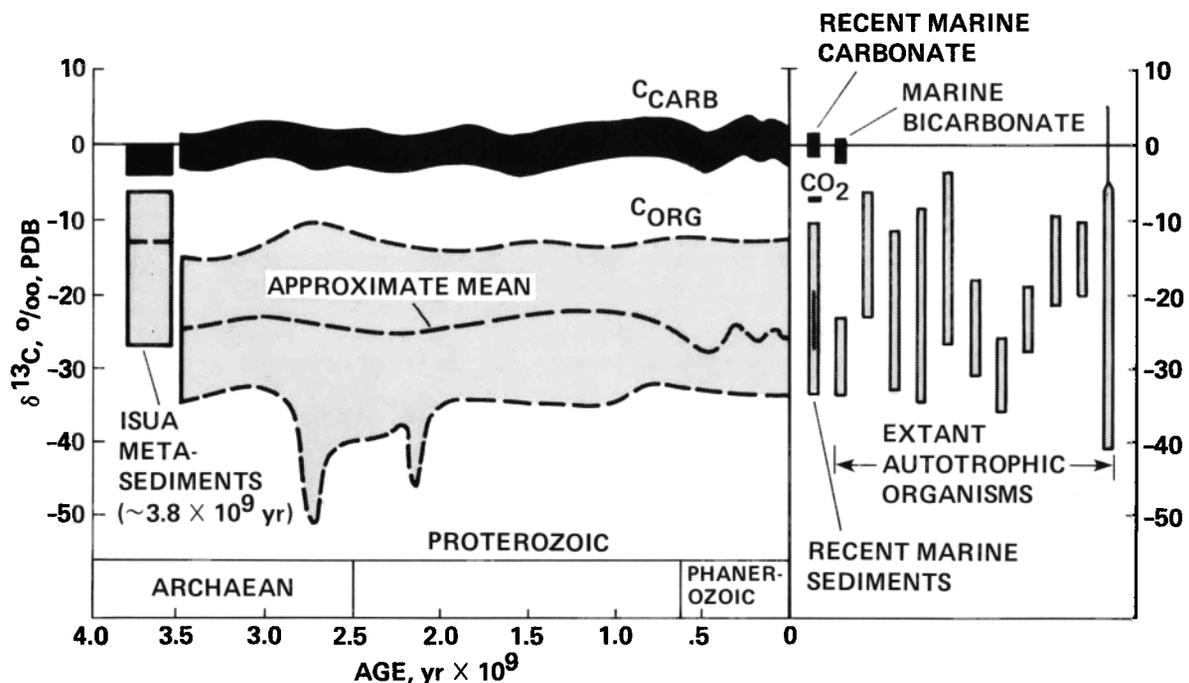


Figure 10. Carbon isotopic values for carbonate and organic sediments on Earth for the last 3.8 Gyr (adapted from *Schidlowski* [1988]). Carbon isotope values are reported in units of permil, which corresponds to the enrichment of the heavy isotope (^{13}C) in parts per thousand, when compared to a standard (Pee Dee belemnite (PDB)). Photosynthetic systems preferentially

uptake ^{12}C over ^{13}C , resulting in an 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.

On Earth, there is evidence that microbial life very quickly split into the three major taxonomic groups of the bacterial world [Woese, 1987]. The universal genetic ancestor common to all three lines is the so-called progenote (see, for example, Woese [1981, 1987]). On the basis of comparing molecular sequences (primarily RNA), phylogenetic trees have been constructed that suggest that the earliest organisms were sulfur-metabolizing thermophiles [Woese, 1987; Lake, 1988]. With only one example of life to study it is hard to tell if this is chance or if there is some evolutionary "reason" for this initial combination of properties. If the earliest organisms on Mars also turn out to have been sulfur-utilizing thermophiles, this would be a significant bit of information. Such information could be obtained from the geological context of Martian fossils.

Proceeding later in evolutionary time, was the endosymbiosis that created the eukaryotic cell [Margulis, 1970] that was ultimately to be the seed for all plants and animals merely a chance event, or would similar circumstances in a similar environment produce similar developments? It is possible that studies of morphologies of Martian microfossils may shed light on these questions. Although most biochemical studies, such as molecular sequencing, would require extant Martian organisms, it is conceivable that organic remains may provide some information on the biochemistry of the early Martian biota.

It is possible that life on Mars developed to a stage that may be comparable to the stromatolites [Awramik, 1971; Awramik *et al.*, 1977]. If so, the record of biological evolution from the earliest universal ancestor to the fairly well developed communities comprising stromatolites (a record that has been destroyed on the Earth) might be found on Mars, and organically preserved microfossils might be identified.

Knoll *et al.* [1986] have reported the discovery of large populations of organically preserved microorganisms associated with silicified carbonate deposits on Earth of age 700–800 million years. This suggests that it is not unreasonable to search for organically preserved fossils in Martian carbonate sediments that may be ~3 Gyr old, since conditions on Mars over geological time may have been conducive to organic preservation. Depending upon the extent of Martian biological evolution, it is even possible, although admittedly unlikely, that information will be preserved that will bear on the question of the rise of the eukaryotic cell and tissue multicellularity, oxygenic photosynthesis, and the buildup of oxygen in the atmosphere.

Chemical Evolution

But perhaps life did not originate on Mars. If prebiotic evolution occurred on Mars but conditions became

unsuitable for life at a very early stage, Mars may give us a glimpse of the conditions that precede life. There are currently two competing paradigms for prebiotic evolution. The "organic" hypothesis is based upon the initial ideas of Oparin [1924, 1936] and Haldane [1928] and on the classic experimental work of Miller [1953, 1955]. In this hypothesis, life originated in an organic-rich primordial soup. The competing hypothesis argues for an "inorganic" origin to the first self-replicating system based upon clay [Cairns-Smith, 1966, 1982; Cairns-Smith and Hartman, 1986]. This early clay life-form subsequently developed into the biochemically based life we see today. Mars, as previously mentioned, is probably rich in clay minerals (see also Huguenin [1974]), and any abiotic sources of organic material that may have been operative on early Earth should have also been operative on early Mars. Thus if Mars' evolution was arrested very early in its biological development, a detailed examination of the organic and inorganic geochemistry of the Martian sediments may resolve questions, as yet unanswered, about prebiotic evolution. Since we apparently have no record of this stage of evolution preserved on Earth, it is not yet clear how to design instruments or experiments to search for this chemical record in Martian rocks.

The Importance of a Negative Result

A third possibility is a completely negative result: neither life nor any relevant form of prebiotic evolution occurred on Mars. If a thorough examination of the Martian surface indicates that there was no life or prebiotic evolution on primordial Mars, then our present model of the physical evolution of the Martian environment may be incorrect, and a suitable environment may never have existed. This would increase our knowledge of Mars, but it would have minimal impact on our understanding of the origin or evolution of life. Alternatively, if it was confirmed that early Mars and early Earth did indeed enjoy similarly hospitable environments for long periods of time and life still did not originate on Mars, then that finding would call into question our entire paradigm for the origin and early evolution of life on Earth. In many ways this would be a stunning and significant result. It would certainly prompt a more in-depth comparison of early Earth and early Mars in an effort to determine just what critical environmental or planetary factor, which is not now considered biologically important, could account for the disparate biological histories.

As an aside, if we find that life did evolve on Mars, reached a fair degree of microbiological sophistication (for example, stromatolites), and subsequently went extinct, this would certainly impact on Lovelock's [1979] Gaia hypothesis that life, once established, controls its planetary environment.

FUTURE MISSIONS AND THE SEARCH FOR MARS' EARLIEST BIOSPHERE

Missions to the Martian surface and ultimately a returned sample for analysis in laboratories on Earth [Drake *et al.*, 1987] will be required to address the scientific questions raised in this paper concerning the possible origin and evolution of life on Mars. Site selection will be an important part of the planning for these missions. From an exobiology perspective, site selection should be based upon the indication of past or present water. Water is the most direct link between biological processes and chemical indicators and is the one universal material requirement of life on Earth. Consequently, there are at least three types of sites that are of interest to exobiology on Mars: (1) sites where water was present in the first billion years of Martian history (sites of this type have already been identified by geomorphological analysis); (2) sites where water activity may be occurring at the present, probably associated with concentrated brine solution resupplied by diffusion from below; and (3) sites near the polar regions where water is being seasonally deposited and sublimed as ice.

The sediments at the bottom of paleolakes, as suggested in previous sections, may be ideal locales to search for evidence of past biological activity. A lake environment is well suited to life, and liquid water can persist under an ice cover long after ambient temperatures fall below freezing. The accumulation of detrital material and sediment on the 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.

Sediments deposited in aquatic environments may be identified from orbit or from the surface by the detection of stratified geological formations. Samples collected from depth could be analyzed for organic material and precipitates such as carbonates using pyrolysis techniques with analysis of the evolved gases.

Direct detection of microscopic fossils on a robotic mission is improbable; such fossils are difficult to detect and identify on Earth. However, one of the main indicators of the presence of microbial life on the early Earth is stromatolites. As discussed above, these are macroscopic structures produced by phototrophic microorganisms, and it is not unreasonable to suggest that they could have occurred on Mars [Awramik, 1989]. These structures could be detected with imaging systems on surface vehicles.

If interesting samples are found on Mars that hold open the possibility of a past biological history, it will probably require analysis of these samples in laboratories on Earth in order to convincingly demonstrate their biological origin. In addition, much more sophisticated analysis, such as searches for microfossils, could be performed on returned samples than would be practical on robotic missions. Since the amount of sample returned would be limited and since sample acquisition would have to be done remotely, even a sample return mission may not provide the critical information needed to unravel the chemical evolution and biological history on Mars. Human missions, with field scientists moving about the Martian surface, may be required to fully understand the Martian fossil record and to determine if the origin of life is preserved in that record.

CONCLUSIONS

Our current understanding of the climatic history of Mars suggests that billions of years ago the Martian environment may have been similar to the environment on Earth at that time. The valley networks, indicative of slowly flowing water, are the most obvious remnant of this early clement period. The duration of clement conditions on early Mars may have been comparable to, or longer than, the time required for life to have evolved on early Earth. Thus the question of the possible origin of life on Mars has become a topic of serious interest.

While the early Martian environment may have been conducive to life, conditions have deteriorated over time, albeit with the possibility of occasional periodic or episodic amelioration of conditions. Martian life may have gone extinct, or it may have developed adaptive strategies unknown to life on Earth that have allowed it to survive in isolated habitats, or in highly resistant dormant stages, to the present time. We have insufficient data to test this hypothesis, and strictly speaking, the question of extant life on Mars remains open.

To address the exobiological questions regarding Mars requires first an understanding of the climatological and geochemical history of that planet. In this paper we have tried to illustrate those areas in which biological investigations are closely coupled to the physical models of Mars' evolution. Some of these areas are as follows: (1) the hydrological cycle of early Mars; (2) the duration of clement conditions (defined by liquid water) on Mars; (3) the abundance and fate of nitrogen on early Mars; (4) the timing, nature, and magnitude of episodic changes in Martian climate; and (5) the location of carbonates and nitrates on Mars.

The study of the biological and environmental history of Mars, whether life originated there or not, will provide us

with new insights into the coevolution of planets and life. Clearly, this effort in planetary science will require strong support from both the biological and the physical sciences. But the payoff is enormous; the origin of life, in the cosmic context, is a profound question in science and human civilization and provides a strong motivation for sending machines and eventually humans to our neighboring planet, Mars.

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REFERENCES

- Anders, E., and T. Owen, Mars and Earth: Origin and abundance of volatiles, *Science*, 198, 453–465, 1977.
- Awramik, S. M., Precambrian columnar stromatolite diversity: Reflection of metazoan appearance, *Science*, 174, 825–827, 1971.
- Awramik, S. M., The pre-Phanerozoic biosphere—Three billion years of crises and opportunities, in *Biotic Crises in Ecological and Evolutionary Time*, edited by M. H. Nitecki, pp. 83–102, Academic, San Diego, Calif., 1981.
- Awramik, S. M., Earth's early fossil record: Why not look for similar fossils on Mars? (abstract), *Exobiology and Future Mars Missions*, edited by C. P. McKay and W. L. Davis, *NASA Conf. Publ.*, 10027, 4–5, 1989.
- Awramik, S. M., L. Margulis, and E. S. Barghoorn, Evolutionary processes in the formation of stromatolites, in *Stromatolites*, edited by M. R. Walter, pp. 149–162, Elsevier, New York, 1976.
- Awramik, S. M., C. D. Gebelein, and P. Cloud, Biogeographic relationships of ancient stromatolites and modern analogs, in *Environmental Biogeochemistry and Geomicrobiology*, edited by W. E. Krumbein, pp. 165–178, Butterworth, Stoneham, Mass., 1977.
- Awramik, S. M., J. W. Schopf, and M. R. Walter, Filamentous fossil bacteria from the Archean of western Australia, *Precambrian Res.*, 20, 357–374, 1983.
- Baker, V. R., *The Channels of Mars*, University of Texas Press, Austin, 1982.
- Baker, V. R., and D. J. Milton, Erosion by catastrophic floods on Mars and Earth, *Icarus*, 23, 27–41, 1974.
- Ballou, E. V., T. C. Wood, T. Wydeven, M. E. Lehwalt, and R. E. Mack, Chemical interpretation of Viking Lander 1 life detection experiment, *Nature*, 271, 644–645, 1978.
- Banin, A., Clays on Mars, in *Clay Minerals and the Origin of Life*, edited by A. G. Cairns-Smith and H. Hartman, pp. 106–115, Cambridge University Press, New York, 1986.
- Banin, A., and L. Margulies, Simulation of Viking biology experiments suggests smectites, not palagonite, as Martian soil analogs, *Nature*, 305, 523–526, 1983.
- Banin, A., and J. Navrot, Chemical fingerprints of life in terrestrial soils and their possible use for the detection of life on Mars and other planets, *Icarus*, 37, 347–350, 1979.
- Barghoorn, E. S., A. H. Knoll, H. Dembicki, Jr., and W. G. Meinschein, Variation in stable carbon isotopes in organic matter from the Gunflint Iron Formation, *Geochim. Cosmochim. Acta*, 41, 425–430, 1977.
- Becker, R. H., and R. O. Pepin, The case for a Martian origin of the shergottites: Nitrogen and noble gases in EETA 79001, *Earth Planet. Sci. Lett.*, 69, 225–242, 1984.
- Biemann, K., J. Oro, P. Toulmin III, L. E. Orgel, A. O. Nier, D. M. Anderson, P. G. Simmonds, D. Flory, A. V. Diaz, D. R. Rushneck, J. E. Biller, and A. L. LaFleur, The search for organic substances and inorganic volatile compounds in the surface of Mars, *J. Geophys. Res.*, 82, 4641–4658, 1977.
- Bogard, D. D., and P. Johnson, Martian gases in an Antarctic meteorite?, *Science*, 221, 651–654, 1983.
- Booth, M. C., and H. H. Kieffer, Carbonate formation in Marslike environments, *J. Geophys. Res.*, 83, 1809–1815, 1978.
- Borucki, W. J., and W. L. Chameides, Lightning: Estimates of the rates of energy dissipation and nitrogen fixation, *Rev. Geophys.*, 22, 363–372, 1984.
- Brock, T. D., *Thermophilic Microorganisms and Life at High Temperatures*, Springer-Verlag, New York, 1978.
- Cairns-Smith, A. G., The origin of life and the nature of the primitive gene, *J. Theor. Biol.*, 10, 53–88, 1966.
- Cairns-Smith, A. G., *Genetic Takeover and the Mineral Origins of Life*, Cambridge University Press, New York, 1982.
- Cairns-Smith, A. G., and H. Hartman, *Clay Minerals and the Origin of Life*, 193 pp., Cambridge University Press, New York, 1986.
- Calder, J. A., and P. L. Parker, Geochemical implications of induced changes in ¹³C fractionation by bluegreen algae, *Geochim. Cosmochim. Acta*, 37, 133–140, 1973.
- Campbell, S. E., Precambrian endoliths discovered, *Nature*, 299, 429–431, 1982.
- Carr, M. H., Tectonism and volcanism of the Tharsis region of Mars, *J. Geophys. Res.*, 79, 3943–3949, 1974.
- Carr, M. H., Formation of Martian flood features by release of water from confined aquifers, *J. Geophys. Res.*, 84, 2995–3007, 1979.
- Carr, M. H., *The Surface of Mars*, Yale University Press, New Haven, Conn., 1981.
- Carr, M. H., Periodic climate changes on Mars: Review of evidence and effects on distribution of volatiles, *Icarus*, 50, 129–139, 1982.
- Carr, M. H., Stability of streams and lakes on Mars, *Icarus*, 56, 476–495, 1983.
- Carr, M. H., Mars: A water-rich planet, *Icarus*, 68, 187–216, 1986.
- Carr, M. H., Water on Mars, *Nature*, 326, 30–35, 1987.
- Carr, M. H., Recharge of the early atmosphere of Mars by impact induced release of CO₂, *Icarus*, 79, 311–327, 1989.
- Carr, M. H., and G. D. Clow, Martian channels and valleys: Their characteristics, distribution, and age, *Icarus*, 48, 91–117, 1981.
- Cess, R. D., V. Ramanathan, and T. Owen, The Martian paleoclimate and enhanced carbon dioxide, *Icarus*, 41, 159–165, 1980.
- Chyba, C. F., S. W. Squyres, and C. Sagan, Oxidant diffusion in the Martian regolith (abstract), *Bull. Am. Astron. Soc.*, 20, 846, 1988.
- Clark, B. C., Implications of abundant hygroscopic minerals in the Martian regolith, *Icarus*, 34, 645–665, 1978.
- Clark, B. C., Solar-driven chemical energy source for a Martian biota, *Origins Life*, 9, 241–249, 1979.
- Clark, B. C., and A. K. Baird, Volatiles in the Martian regolith, *Geophys. Res. Lett.*, 6, 811–814, 1979.
- Clark, B. C., and D. C. Van Hart, The sales to Mars, *Icarus*, 45, 370–387, 1981.
- Clark, B. C., A. K. Baird, R. J. Weldon, D. M. Tsusaki, L. Schnabel, and M. P. Candelaria, Chemical composition of Martian fines, *J. Geophys. Res.*, 87, 10,059–10,067, 1982.

- Clifford, S. M., Polar basal melting on Mars, *J. Geophys. Res.*, 92, 9135–9152, 1987.
- Clifford, S. M., and D. Hillel, The stability of ground ice in the equatorial region of Mars, *J. Geophys. Res.*, 88, 2456–2474, 1983.
- Clow, G. D., Generation of liquid water on Mars through the melting of a dusty snowpack, *Icarus*, 72, 95–127, 1987.
- Clow, G. D., C.P. McKay, G. M. Simmons, Jr., and R. A. Wharton, Jr., Climatological observations and predicted sublimation rates at Lake Hoare, Antarctica, *J. Clim.*, 1, 715–728, 1988.
- Crowe, J. H., and J. S. Clegg, *Dry Biological Systems*, Academic, San Diego, Calif., 1978.
- Crowe, L. M., and J. H. Crowe, Life without water (abstract), Exobiology and Future Mars Missions, edited by C. P. McKay and W. L. Davis, *NASA Conf. Publ.*, 10027, 13–14, 1989.
- Davies, G. F., and R. E. Arvidson, Martian thermal history, core segregation, and tectonics, *Icarus*, 45, 339–346, 1981.
- Davis, B. W., Some speculations on adsorption and desorption of CO₂ in Martian bright areas, *Icarus*, 11, 155–158, 1969.
- DesMarais, D. J., J. H. Donchin, N. L. Nehring, and A. H. Truesdell, Molecular carbon isotope evidence for the origin of geothermal hydrocarbons, *Nature*, 292, 826–828, 1981.
- DeVincenzi, D. L., NASA's exobiology program, *Origins Life*, 14, 793–799, 1984.
- Drake, M. J., W. V. Boynton, and D. P. Blanchard, The case for planetary sample return missions, 1, Origin of the solar system, *Eos Trans. AGU*, 68, 105–113, 1987.
- Dreibus, G., and H. Wänke, Volatiles on Earth and Mars, A comparison, *Icarus*, 71, 225–240, 1987.
- Estep, M. L. F., Carbon and hydrogen isotopic compositions of algae and bacteria from hydrothermal environments, Yellowstone National Park, *Geochim. Cosmochim. Acta*, 48, 591–599, 1984.
- Estep, M. L. F., F. R. Tabita, P. L. Parker, and C. Van Baalen, Carbon isotope fractionation by ribulose-1, 5-bisphosphate carboxylase from various organisms, *Plant Physiol.*, 61, 680–687, 1978.
- Fanale, F. P., Martian volatiles, their degassing history and geochemical fate, *Icarus*, 28, 179–202, 1976.
- Fanale, F. P., and W. A. Cannon, Exchange of adsorbed H₂O and CO₂ between the regolith and atmosphere of Mars caused by changes in surface insulation, *J. Geophys. Res.*, 79, 3397–3402, 1974.
- Fanale, F. P., and W. A. Cannon, Mars: CO₂ adsorption and capillary condensation on clays—Significance for volatile storage and atmospheric history, *J. Geophys. Res.*, 84, 8404–8414, 1979.
- Fanale, F. P., J. R. Salvail, W. B. Banerdt, and R. S. Saunders, The regolith-atmosphere-cap system and climate change, *Icarus*, 50, 381–407, 1982.
- Fanale, F. P., J. R. Salvail, A. P. Zent, and S. E. Postawko, Global distribution and migration of subsurface ice on Mars, *Icarus*, 67, 1–18, 1986.
- Fox, J. L., and A. Dalgarno, Nitrogen escape from Mars, *J. Geophys. Res.*, 88, 9027–9032, 1983.
- Friedmann, E. I., Endolithic microbial life in hot and cold deserts, *Origins Life*, 10, 223–235, 1980.
- Friedmann, E. I., Endolithic microorganisms in the Antarctic cold desert, *Science*, 215, 1045–1053, 1982.
- Friedmann, E. I., The Antarctic cold desert and the search for traces of life on Mars, *Adv. Space Res.*, 6, 265–268, 1986.
- Friedmann, E. I., and R. Ocampo, Endolithic blue-green algae in the dry valleys: Primary producers in the Antarctic cold desert ecosystem, *Science*, 193, 1247–1249, 1972.
- Friedmann, E. I., C. P. McKay, and J. A. Nienow, The cryptoendolithic microbial environment in the Ross Desert of Antarctica: Nanoclimate data, 1984 to 1986, *Polar Biol.*, 7, 273–287, 1987.
- Goldspiel, J. M., and S. W. Squyres, Ancient lakes in Mars? (abstract), Exobiology and Future Mars Missions, edited by C. P. McKay and W. L. Davis, *NASA Conf. Publ.*, 10027, 26, 1989.
- Golubic, S., The relationship between blue-green algae and carbonate deposits, in *The Biology of Blue-green Algae*, edited by N. C. Carr and B. A. Whitton, pp. 434–472, University of California Press, Berkeley, 1973.
- Golubic, S., Organisms that build stromatolites, in *Stromatolites*, edited by M. R. Walter, pp. 113–126, Elsevier, New York, 1976.
- Gooding, J. L., Chemical weathering on Mars: Thermodynamic stabilities of primary minerals (and their alteration products) from mafic igneous rocks, *Icarus*, 33, 483–513, 1978.
- Gooding, J. L., S. J. Wentworth, and M. E. Zolensky, Calcium carbonate and sulfate of possible extraterrestrial origin in the EETA79001 meteorite, *Geochim. Cosmochim. Acta*, 52, 909–915, 1988.
- Greeley, R., Release of juvenile water on Mars: Estimated amounts and timing associated with volcanism, *Science*, 236, 1653–1654, 1987.
- Greeley, R., and P. D. Spudis, Volcanism on Mars, *Rev. Geophys.*, 19, 13–41, 1981.
- Haldane, J. B. S., The origin of life, *Ration. Ann.*, 148, 3–10, 1928.
- Hart, H., and B. M. Jakosky, Composition and stability of the condensate observed at the Viking Lander 2 site on Mars, *Icarus*, 66, 134–142, 1986.
- Hartmann, W. K., Martian cratering, 4, Mariner 9 initial analysis of cratering chronology, *J. Geophys. Res.*, 78, 4096–4116, 1973.
- Head, J. W., and S. C. Solomon, Tectonic evolution of the terrestrial planets, *Science*, 213, 62–76, 1981.
- Hess, S. L., R. M. Henry, and J. E. Tillman, The seasonal variation of atmospheric pressure on Mars as affected by the south polar cap, *J. Geophys. Res.*, 84, 2923–2927, 1979.
- Hess, S. L., J. A. Ryan, J. E. Tillman, R. M. Henry, and C. B. Leovy, The annual cycle of pressure on Mars measured by Viking landers 1 and 2, *Geophys. Res. Lett.*, 7, 197–200, 1980.
- Hoffert, M. I., A. J. Callegari, C. T. Hsieh, and W. Ziegler, Liquid water on Mars: An energy balance climate model for CO₂/H₂O atmospheres, *Icarus*, 47, 112–129, 1981.
- Hoham, R. W., Optimum temperatures and temperature ranges for growth of snow algae, *Arct. Alpine Res.*, 7, 13–24, 1975.
- Hoham, R. W., J. E. Mullet, and S. C. Roemer, The life history and ecology of the snow alga *Chloromonas polyptera* comb. nov. (Chlorophyta, Volvocales), *Can. J. Bot.*, 61, 2416–2429, 1983.
- Holland, H. D., *The Chemical Evolution of the Atmosphere and Oceans*, Princeton University Press, Princeton, N. J., 1984.
- Horowitz, N. H., The search for life on Mars, *Sci. Am.*, 237, 52–61, 1977.
- Horowitz, N. H., *To Utopia and Back: The Search for Life in the Solar System*, W. H. Freeman, New York, 1986.
- Horowitz, N. H., and G. L. Hobby, Viking on Mars: The carbon assimilation experiments, *J. Geophys. Res.*, 82, 4659–4662, 1977.
- Huguenin, R. L., The formation of goethite and hydrated clay minerals on Mars, *J. Geophys. Res.*, 79, 3895–3905, 1974.
- Huguenin, R. L., Mars: Chemical weathering as a massive volatile sink, *Icarus*, 28, 203–212, 1976.
- Huguenin, R. L., K. J. Miller, and W. S. Harwood, Frost-weathering on Mars: Experimental evidence for peroxide formation, *J. Mol. Evol.*, 14, 103–132, 1979.
- Hunten, D. M., Possible oxidant sources in the atmosphere and surface of Mars, *J. Mol. Evol.*, 14, 57–64, 1979.
- Ingersoll, A. P., Mars: Occurrence of liquid water, *Science*, 168, 972–973, 1970.
- Jakosky, B. M., and C. B. Farmer, The seasonal and global

- behavior of water vapor in the Mars atmosphere: Complete global results of the Viking atmospheric water detector experiment, *J. Geophys. Res.*, **87**, 2999–3019, 1982.
- Jensen, B., and R. Cox, Direct steady state kinetics of cyanobacteria N_2 uptake by membrane-leak mass spectrometry, and comparisons between nitrogen fixation and acetylene reduction, *Appl. Environ. Microbiol.*, **45**, 1331–1337, 1983.
- Kahn, R., The evolution of CO_2 on Mars, *Icarus*, **62**, 175–190, 1985.
- Karl, D. M., C. O. Wirsen, and H. W. Jannasch, Deep-sea primary production at the Galapagos hydrothermal vents, *Science*, **207**, 1345–1347, 1980.
- Kasting, J. F., Stability of ammonia in the primitive terrestrial atmosphere, *J. Geophys. Res.*, **87**, 3091–3098, 1982.
- Kasting, J. F., and T. P. Ackerman, Climatic consequences of very high CO_2 levels in Earth's early atmosphere, *Science*, **234**, 1383–1385, 1986.
- Klein, H. P., The Viking biological experiments on Mars, *Icarus*, **34**, 666–674, 1978.
- Klein, H. P., The Viking mission and the search for life on Mars, *Rev. Geophys.*, **17**, 1655–1662, 1979.
- Knoll, A. H., S. Golubic, J. Green, and K. Swett, Organically preserved microbial endoliths from the late Proterozoic of East Greenland, *Nature*, **321**, 856–857, 1986.
- Kuhn, W. R., and S. W. Atreya, Ammonia photolysis and the greenhouse effect in the primordial atmosphere of the Earth, *Icarus*, **37**, 207–213, 1979.
- Kushner, D., Extreme environments: Are there any limits to life?, in *Comets and the Origin of Life*, edited by C. Ponnamperuma, pp. 241–248, D. Reidel, Hingham, Mass., 1981.
- Lake, J. A., Origin of the eukaryotic nucleus determined by rate-invariant analysis of rRNA sequences, *Nature*, **331**, 184–186, 1988.
- Lederberg, J., Exobiology: Approaches to life beyond the Earth, *Science*, **132**, 393–400, 1960.
- Levin, G. V., A reappraisal of life on Mars, proceedings of the NASA Mars conference, *Am. Astron. Soc.*, **71**, 187–207, 1988.
- Levin, G. V., and P. A. Straat, Recent results from the Viking Labeled Release Experiment on Mars, *J. Geophys. Res.*, **82**, 4663–4667, 1977.
- Levin, G. V., and P. A. Straat, A search for nonbiological explanation of the Viking Labeled Release Life Detection Experiment, *Icarus*, **45**, 494–516, 1981.
- Levine, J. S., The photochemistry of the early Earth, in *The Photochemistry of Atmospheres*, edited by J. S. Levine, pp. 3–38, Academic, San Diego, Calif., 1985.
- Levine, J. S., T. R. Augustsson, and M. Natarajan, The prebiological paleoatmosphere: Stability and composition, *Origins Life*, **12**, 245–259, 1982a.
- Levine, J. S., G. L. Gregory, G. A. Harvey, W. E. Howell, W. J. Borucki, and R. E. Orville, Production of nitric oxide by lightning on Venus, *Geophys. Res. Lett.*, **9**, 893–896, 1982b.
- Lewis, J. S., Metal/silicate fraction in the solar system, *Earth Planet. Sci. Lett.*, **15**, 286–290, 1972.
- Liu, S., and T. M. Donahue, The regulation of hydrogen and oxygen escape from Mars, *Icarus*, **28**, 231–246, 1976.
- Lorimer, G. H., The carboxylation and oxygenation of ribulose 1,5-bisphosphate: The primary events in photosynthesis and photorespiration, *Annu. Rev. Plant Physiol.*, **32**, 349–383, 1981.
- Love, F. G., G. M. Simmons, Jr., R. A. Wharton, Jr., B. C. Parker, and K. G. Seaburg, Modern *Conophyton*-like algal mats discovered in Lake Vanda, Antarctica, *Geomicrobiol. J.*, **3**, 33–48, 1983.
- Lovelock, J. E., *Gaia*, Oxford University Press, New York, 1979.
- Lucchitta, B. K., Lakes or playas in Valles Marineris (abstract), *NASA Tech. Memo. 84211*, pp. 233–234, 1981.
- Lucchitta, B. K., Recent mafic volcanism on Mars, *Science*, **235**, 565–567, 1987.
- Lucchitta, B. K., and H. M. Ferguson, Chryse Basin channels: Low gradients and ponded flows, *Proc. Lunar Planet. Sci. Conf. 13th, Part 2, J. Geophys. Res.*, **88**, suppl. A553–A586, 1983.
- Maher, K. A., and D. J. Stevenson, Impact frustration of the origin of life, *Nature*, **331**, 612–614, 1988.
- Mancinelli, R. L., and C. P. McKay, The evolution of nitrogen cycling, *Origins Life*, **18**, 311–325, 1988.
- Margulis, L., *Origin of Eucaryotic Cells*, Yale University Press, New Haven, Conn., 1970.
- Masursky, H., J. M. Boyce, A. L. Dial, G. G. Schaber, and M. E. Strobel, Classification and time of formation of Martian channels based on Viking data, *J. Geophys. Res.*, **82**, 4016–4038, 1977.
- Masursky, H., M. G. Chapman, P. A. Davis, A. L. Dial, Jr., and M. E. Strobel, Martian terrains, *NASA Tech. Memo. TM-89810*, pp. 545–547, 1987.
- Mazur, P., Limits to life at low temperatures and at reduced water contents and water activities, *Origins Life*, **10**, 137–159, 1980.
- Mazur, P., E. S. Barghoorn, H. O. Halvorson, T. H. Jukes, I. R. Kaplan, and L. Margulis, Biological implications of the Viking mission to Mars, *Space Sci. Rev.*, **22**, 3–34, 1978.
- McCauley, J. F., Geologic map of the Coprates Quadrangle of Mars, *U. S. Geol. Surv. Misc. Invest. Ser. Map, 1-897*, 1978.
- McCord, T. M., R. N. Clark, and R. B. Singer, Mars: Near-infrared spectral reflectance of surface regions and compositional implications, *J. Geophys. Res.*, **87**, 3021–3032, 1982.
- McElroy, M. B., T. Y. Kong, and Y. L. Yung, Photochemistry and evolution of Mars' atmosphere: A Viking perspective, *J. Geophys. Res.*, **82**, 4379–4388, 1977.
- McKay, C. P., Exobiology and future Mars missions: The search for Mars' earliest biosphere, *Adv. Space Res.*, **6**, 269–285, 1986.
- McKay, C. P., and S. S. Nedell, Are there carbonate deposits in Valles Marineris, Mars?, *Icarus*, **73**, 142–148, 1988.
- McKay, C. P., G. D. Clow, R. A. Wharton, Jr., and S. W. Squyres, Thickness of ice on perennially frozen lakes, *Nature*, **313**, 561–562, 1985.
- Miller, S. L., A production of amino acids under possible primitive Earth conditions, *Science*, **117**, 528–529, 1953.
- Miller, S. L., Production of some organic compounds under possible primitive Earth conditions, *J. Am. Chem. Soc.*, **77**, 2351–2361, 1955.
- Miller, S. M., and L. E. Orgel, *The Origins of Life on the Earth*, Prentice-Hall, Englewood Cliffs, N. J., 1974.
- Mouginis-Mark, P. J., Water or ice in the Martian regolith?: Clues from rampart craters seen at very high resolution, *Icarus*, **71**, 268–286, 1987.
- Neelson, K. H., Microbiological oxidation and reduction of iron, in *Mineral Deposits and the Evolution of the Biosphere*, edited by H. D. Holland and M. Schidlowski, pp. 51–65, Springer-Verlag, New York, 1982.
- Nedell, S. S., S. W. Squyres, and D. W. Andersen, Origin and evolution of the layered deposits in the Valles Marineris, Mars, *Icarus*, **70**, 409–441, 1987.
- O'Leary, M. H., Carbon isotope fractionation in plants, *Phytochemistry*, **20**, 553–567, 1981.
- Oparin, A. I., *Proiskhozhdenie Zhizni*, Isd. Moskovskii Rabotchii, Moscow, 1924.
- Oparin, A. I., *The Origin of Life*, Macmillan, New York, 1936.
- Oró, J., and G. Holzer, The photolytic degradation and oxidation of organic compounds under simulated Martian conditions, *J. Mol. Evol.*, **14**, 153–160, 1979.
- Owen, T., K. Biemann, D. R. Rushnek, J. E. Biller, D. W. Howarth, and A. L. Lafleur, The composition of the

- atmosphere at the surface of Mars, *J. Geophys. Res.*, **82**, 4635–4639, 1977.
- Owen, T., R. D. Cess, and V. Ramanathan, Enhanced CO₂ greenhouse to compensate for reduced solar luminosity on early Earth, *Nature*, **277**, 640–642, 1979.
- Owen, T., J. P. Maillard, C. de Bergh, and B. L. Lutz, Deuterium on Mars: The abundance of HDO and the value of D/H, *Science*, **240**, 1767–1770, 1988.
- Oyama, V. I., and B. J. Berdahl, The Viking Gas Exchange Experiment results from Chryse and Utopia surface samples, *J. Geophys. Res.*, **82**, 4669–4676, 1977.
- Oyama, V. I., and B. J. Berdahl, A model of Martian surface chemistry, *J. Mol. Evol.*, **14**, 199–210, 1979.
- Pang, K. D., S. F. S. Chun, J. M. Ajello, Z. Nansheng, and L. Minji, Organic and inorganic interpretations of the Martian UV-IR reflectance spectrum, *Nature*, **295**, 43–46, 1982.
- Parker, B. C., G. M. Simmons, Jr., F. G. Love, R. A. Wharton, Jr., and K. G. Seaburg, Modern stromatolites in Antarctic dry valley lakes, *BioScience*, **31**, 656–661, 1981.
- Parker, B. C., G. M. Simmons, Jr., K. G. Seaburg, D. D. Cathey, and F. T. C. Allnut, Comparative ecology of plankton communities in seven Antarctic oasis lakes, *J. Plankton Res.*, **4**, 271–286, 1982.
- Pepin, R. O., Volatile inventories of the terrestrial planets, *Rev. Geophys.*, **25**, 293–296, 1987.
- Pieri, D., Distribution of small channels on the Martian surface, *Icarus*, **27**, 25–50, 1976.
- Pieri, D., Martian valleys: Morphology, distribution, age, and origin, *Science*, **210**, 895–897, 1980.
- Pollack, J. B., Climate change on the terrestrial planets, *Icarus*, **37**, 479–533, 1979.
- Pollack, J. B., and D. C. Black, Implications of the gas compositional measurements of Pioneer Venus for the origin of planetary atmospheres, *Science*, **205**, 56–59, 1979.
- Pollack, J. B., and D. C. Black, Noble gases in planetary atmospheres: Implications for the origin and evolution of atmospheres, *Icarus*, **51**, 169–198, 1982.
- Pollack, J. B., and O. B., Toon, Quasi-periodic climate changes on Mars: A review, *Icarus*, **50**, 259–287, 1982.
- Pollack, J. B., and Y. L. Yung, Origin and evolution of planetary atmospheres, *Annu. Rev. Earth Planet. Sci.*, **8**, 425–487, 1980.
- Pollack, J. B., J. F. Kasting, S. M. Richardson, and K. Poliakoff, The case for a wet, warm climate on early Mars, *Icarus*, **71**, 203–224, 1987.
- Postawko, S. E., and W. R. Kuhn, Effect of the greenhouse gases (CO₂, H₂O, SO₂) on Martian paleoclimate, *Proc. Lunar Planet. Sci. Conf. 16th*, *J. Geophys. Res.*, **91**, suppl. D431–D438, 1986.
- Rasool, S. I., and L. LeSergeant, Volatile outgassing from Earth and Mars: Implications of the Viking results, *Nature*, **266**, 822–823, 1977.
- Robbins, E. I., *Appellella ferrifera*, a possible new iron-coated microfossil in the Isua iron-formation, southwestern Greenland, in *Precambrian Iron-Formations*, edited by P. W. Uitterdijk Appel and G. L. LaBerge, pp. 141–154, Theophrastus Publications, Athens, Greece, 1987.
- Rossbacher, L. A., and S. Judson, Ground ice on Mars: Inventory, distribution and resulting landforms, *Icarus*, **45**, 25–38, 1981.
- Roush, T. L., D. Blaney, T. B. McCord, and R. B. Singer, Carbonates on Mars: Searching the Mariner 6 and 7 IRS measurements (abstract), *Lunar Planet. Sci.*, **XVII**, 732–733, 1986.
- Sagan, C., Reducing greenhouses and the temperature history of Earth and Mars, *Nature*, **269**, 224–226, 1977.
- Sagan, C., and G. Mullen, Earth and Mars: Evolution of atmospheres and surface temperatures, *Science*, **177**, 52–56, 1972.
- Schidlowski, M., A 3,800-million-year isotopic record of life from carbon in sedimentary rocks, *Nature*, **333**, 313–318, 1988.
- Schidlowski, M., J. M. Hayes, and I. R. Kaplan, Isotopic inferences of ancient biochemistries: Carbon, sulphur, hydrogen, and nitrogen, in *Earth's Earliest Biosphere; Its Origin and Evolution*, edited by J. W. Schopf, Princeton University Press, Princeton, N. J., 1983.
- Schopf, J. W. (Ed.), *Earth's Earliest Biosphere; Its Origin and Evolution*, Princeton University Press, Princeton, N.J., 1983.
- Schopf, J. W., and B. M. Packer, Early Archean (3.3-billion to 3.5-billion-year-old) microfossils from Warrawoona Group, Australia, *Science*, **237**, 70–73, 1987.
- Schultz, P. H., and D. E. Gault, Atmospheric effects on Martian ejecta emplacement, *J. Geophys. Res.*, **84**, 7669–7687, 1979.
- Singer, R. B., Spectroscopic observations of Mars, *Adv. Space Res.*, **5**, 59–68, 1985.
- Soderblom, L. A., and D. B. Wenner, Possible fossil H₂O liquid-ice interfaces in the Martian crust, *Icarus*, **34**, 622–637, 1978.
- Soderblom, L. S., C. D. Condit, R. A. West, B. M. Herman, and T. J. Kriedler, Martian planet-wide crater distributions: Implications for geologic history and surface processes, *Icarus*, **22**, 239–263, 1974.
- Solomon, S. C., On volcanism and thermal tectonics on one-plate planets, *Geophys. Res. Lett.*, **5**, 461–464, 1978.
- Squyres, S. W., The history of water on Mars, *Annu. Rev. Earth Planet. Sci.*, **12**, 83–106, 1984.
- Squyres, S. W., and M. H. Carr, Geomorphic evidence for the distribution of ground ice on Mars, *Science*, **231**, 249–252, 1986.
- Stoker, C. R., P. J. Boston, R. L. Mancinelli, W. Segal, B. N. Khare, and C. Sagan, Microbial metabolism of tholin, *Icarus*, in press, 1989.
- Tebo, B. M., and S. Emerson, Microbial manganese (II) oxidation in the marine environment: A quantitative study, *Biogeochemistry*, **2**, 149–161, 1986.
- Toksöz, M. N., and A. T. Hsui, Thermal history and evolution of Mars, *Icarus*, **34**, 537–547, 1978.
- Toon, O. B., J. B. Pollack, W. Ward, J. A. Burns, and K. Bilski, The astronomical theory of climate change on Mars, *Icarus*, **44**, 552–607, 1980.
- Toulmin, P., III, A. K. Baird, B. C. Clark, K. Keil, H. J. Rose, Jr., R. P. Christan, P. H. Evans, and W. C. Kelliher, Geochemical and mineralogical interpretations of the Viking inorganic chemical results, *J. Geophys. Res.*, **82**, 4625–4634, 1977.
- Turekian, K. K., and S. P. Clark, Jr., The non-homogeneous accumulation model for terrestrial planet formation and the consequences for the atmosphere of Venus, *J. Atmos. Sci.*, **32**, 1257–1261, 1975.
- Walker, J. C. G., *Evolution of the Atmosphere*, Macmillan, New York, 1977.
- Walker, J. C. G., Carbon dioxide on the early Earth, *Origins Life*, **16**, 117–127, 1985.
- Wallace, D., and C. Sagan, Evaporation of ice in planetary atmospheres: Ice-covered rivers on Mars, *Icarus*, **39**, 385–400, 1979.
- Walter, M. R., and J. Bauld, The association of sulphate evaporites, stromatolitic carbonates and glacial sediments: Examples from the Proterozoic of Australia and the Cainozoic of Antarctica, *Precambrian Res.*, **21**, 129–148, 1983.
- Ward, W. R., Climatic variations on Mars, 1, Astronomical theory of insolation, *J. Geophys. Res.*, **79**, 3375–3385, 1974.
- Ward, W. R., B. C. Murray, and M. C. Malin, Climatic variations on Mars, 2, Evolution of carbon dioxide atmosphere and polar caps, *J. Geophys. Res.*, **79**, 3387–3395, 1974.
- Ward, W. R., J. A. Burns, and O. B. Toon, Climatic variations on Mars, 2, Past obliquity oscillations of Mars: Role of the

- Tharsis uplift, *J. Geophys. Res.*, **84**, 243–259, 1979.
- Wharton, R. A., Jr., Ecology of algal mats and their role in the formation of stromatolites in Antarctic dry valley lakes, Ph. D. dissertation, 103 pp., Va. Tech., Blacksburg, Va., 1982.
- Wharton, R. A., Jr., W. C. Vinyard, B. C. Parker, G. M. Simmons, Jr., and K. G. Seaburg, Algae in cryoconite holes on Canada Glacier in southern Victoria Land, Antarctica, *Phycologia*, **20**, 208–211, 1981.
- Wharton, R. A., Jr., B. C. Parker, G. M. Simmons, Jr., K. G. Seaburg, and F. G. Love, Biogenic calcite structures forming in Lake Fryxell, Antarctica, *Nature*, **295**, 403–405, 1982.
- Wharton, R. A., Jr., B. C. Parker, and G. M. Simmons, Jr., Distribution, species composition and morphology of algal mats in Antarctic dry valley lakes, *Phycologia*, **22**, 355–365, 1983.
- Wharton, R. A., Jr., C. P. McKay, G. M. Simmons, Jr., and B. C. Parker, Cryoconite holes on glaciers, *BioScience*, **35**, 499–503, 1985.
- Wharton, R. A., Jr., C. P. McKay, G. M. Simmons, Jr., and B. C. Parker, Oxygen budget of a perennially ice-covered Antarctic dry valley lake, *Limnol. Oceanogr.*, **31**, 437–443, 1986.
- Wharton, R. A., Jr., C. P. McKay, R. L. Mancinelli, and G. M. Simmons, Jr., Perennial N₂ supersaturation in an Antarctic lake, *Nature*, **325**, 343–345, 1987.
- Wise, D. U., M. P. Golombek, and G. E. McGill, Tectonic evolution of Mars, *J. Geophys. Res.*, **84**, 7934–7939, 1979.
- Woese, C. R., Archaeobacteria, *Sci. Am.*, **244**, 98–122, 1981.
- Woese, C. R., Bacterial evolution, *Microbiol. Rev.*, **51**, 221–271, 1987.
- Wu, S. S. C., P. A. Garcia, R. Jordan, F. J. Schafer, and B. A. Skiff, Topography of the shield volcano, Olympus Mons on Mars, *Nature*, **309**, 432–435, 1984.
- Yung, Y. L., J.-S. Wen, J. P. Pinto, M. Allen, K. K. Pierce, and S. Paulson, HDO in the Martian atmosphere: Implications for the abundance of crustal water, *Icarus*, **76**, 146–159, 1988.
- Zent, A. P., and F. P. Fanale, Possible Mars brines: Equilibrium and kinetic considerations, *Proc. Lunar Planet. Sci. Conf. 16th, Part 2, J. Geophys. Res.*, **91**, suppl. D439–D445, 1986.
- Zent, A. P., F. P. Fanale, and S. E. Postawko, Carbon dioxide: Adsorption on palagonite and partitioning in the Martian regolith, *Icarus*, **71**, 241–249, 1987.
- Zimbelman, J. R., Spatial resolution and the geologic interpretation of Martian morphology: Implications for subsurface volatiles, *Icarus*, **71**, 257–267, 1987.
- Zisk, S. H., and P. J. Mougins-Mark, Anomalous region on Mars: Implications for near-surface liquid water, *Nature*, **288**, 735–738, 1980.

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