

Exploring for a record of ancient Martian life

Jack D. Farmer

Department of Geology, Arizona State University, Tempe

David J. Des Marais

NASA Ames Research Center, Moffett Field, California

Abstract. The immediate task facing exopaleontology is to define a strategy to explore Mars for a fossil record during the decade-long exploration program that lies ahead. Consideration of the quality of paleontological information preserved under different geological conditions is important if we are to develop a strategy with broad applicability. The preservation of microbial fossils is strongly influenced by the physical, chemical, and biological factors of the environment which, acting together, determine the types of information that will be captured and retained in the rock record. In detrital sedimentary systems, preservation is favored by rapid burial in fine-grained, clay-rich sediments. In chemical sedimentary systems, preservation is enhanced by rapid entombment in fine-grained chemical precipitates. For long-term preservation, host rocks must be composed of stable minerals that are resistant to chemical weathering and that form an impermeable matrix and closed chemical system to protect biosignatures from alteration during subsequent diagenesis or metamorphism. In this context, host rocks composed of highly ordered, chemically stable mineral phases, like silica (e.g., cherts) or phosphate (e.g., phosphorites), are especially favored. Such lithologies tend to have very long crustal residence times and, along with carbonates and shales, are the most common host rocks for the Precambrian microfossil record on Earth. Although we make the defensible assumption that Mars was more like the Earth early in its history, clearly, the geological and historical differences between the two planets are many. Such differences must be carefully considered when adapting an Earth-based strategy to Mars.

1. Introduction

The present emphasis in Mars exploration lies in the search for a fossil record [Klein and Farmer, 1995]. On Earth the long-term preservation of fossils occurs under a fairly narrow range of geological conditions [Knoll, 1984; Allison and Briggs, 1991a; Allison and Pye, 1994]. Favored environments share many basic physical and compositional characteristics that serve to guide the search for a microbial fossil record, whether in ancient stratigraphic sequences on Earth or, with appropriate adaptation, on other planetary surfaces like Mars. Because the basic conceptual framework and methodology required for paleontological exploration of other planetary bodies differ substantially from the search for extant life (embraced by the traditional discipline of exobiology), we refer to the former activity as "exopaleontology" [Farmer, 1995].

In this paper we seek to create a historical perspective about the Earth's biosphere that will serve as a practical context for Mars exploration. The early history of the terrestrial biosphere and the factors that control life's limits are important constraints for assessing the probability that Mars developed life. Such constraints also provide a focus for the identification of potential habitable zones (past or present) on Mars.

At the heart our strategy for Mars exopaleontology are those factors that control microbial fossilization on the Earth. An understanding of these factors is crucial for the identification

of those sites on Mars that have the greatest potential for capturing and preserving a fossil record.

The utility of a strategy is best demonstrated by application. Using the Pathfinder mission as an example, we show how the strategy may be applied to landing site selection. Although the Pathfinder mission was not designed to look for life, it certainly provided an interesting opportunity to evaluate the strengths and weaknesses of the conceptual framework and strategy for exopaleontology.

2. Earth's Microbial Biosphere: A Context for Mars Exopaleontology

2.1. The Limits of Life

Since Viking, our knowledge of the environmental limits of life on Earth has expanded dramatically through the development of microanalytical sampling techniques, applied over a wide range of environmental extremes [Nealson, 1997]. The terrestrial model suggests the potential for life elsewhere in the Cosmos is dependent, at least in part, on finding the range of environments within which it can survive here on Earth. A brief summary of known environmental limits to terrestrial life is therefore relevant (Table 1). Liquid water is regarded as essential and dictates the lower temperature at which microbial communities can grow and persist over geological timescales. The currently accepted maximum temperature for the growth of living systems is 113°C for a microbial community in thermal springs at Vulcano, Italy [Stetter, 1996] (note that survival may occur at higher temperatures). The upper temperature limit for life determines its distribution within hydrothermal envi-

Table 1. Extremes for Microbial Growth

Factor	Maximum	Minimum
Temperature, °C	113*	-10†
pH	11	1.5*
Salinity, % NaCl	30*	0
Water activity A_w	1.0	≥0.6*
Pressure, atm	1035*	0.3‡

*Madigan et al. [1996].

†Gilichinsky [1995].

‡Based on elevation of Mt. Everest (8.8 km).

ronments, whether within surface environments as hot springs or deep within the subsurface. The energy requirements of life also determine its distribution and productivity. Photosynthesis directly powers >99% of the modern biosphere's productivity, simply because energy from sunlight, per unit area of the Earth's surface, is several hundred times more abundant than chemical energy derived from thermal and crustal sources [Des Marais, 1997]. Even most chemoautotrophic systems depend indirectly on the Sun through inputs of photosynthetically fixed carbon. Accordingly, life is found virtually anywhere on the Earth where sunlight and liquid water are both present.

As our methods of observation have improved, life's environmental limits have continued to expand. We have discovered that life can also survive in deep subsurface environments where the interaction of water and rock yield available energy. Diverse associations of chemotrophic microbes are known to inhabit a variety of subsurface environments [Pedersen, 1993; Amy and Haldeman, 1997; Fredrickson and Onstott, 1996]. Lithoautotrophic organisms capable of synthesizing organic compounds from inorganic substrates [see Stevens and McKinley, 1996] hold special importance for Mars since surface environments have probably been inclement for most of the planet's history.

2.2. Antiquity of the Earth's Biosphere

During the more than two decades since Viking, discoveries in Precambrian paleontology have pushed back the fossil record of terrestrial life to encompass the oldest sedimentary sequences found on Earth. We now have an undisputed morphological record of microbial life dating from the ~3.45 billion year old Apex Chert of Western Australia [Schopf, 1993]. Furthermore, these earliest microfossil assemblages are diverse, suggesting a period of prior evolution during which microbial life diverged into several major groups. This earlier period of evolution is supported by recently discovered chemofossil evidence for life within the oldest marine sedimentary sequences on Earth, dated at ~3.87 billion years [Mojzsis et al., 1996; see also Schidlowski, 1995]. Model-based arguments suggest that a stable atmosphere and oceans, with surface temperatures <100°C, existed on Earth by 4.4 billion years ago [Chang, 1994, and references therein]. Models for early accretion also suggest early frustration of biosphere development by late, giant impacts, the last of which could have occurred ~3.9 billion years ago [Sleep et al., 1989; see also Sleep and Zahnle, 1998]. These constraints greatly narrow the time available for the origin of life. The implication is that under Earth-like conditions, life can originate quickly, in a few hundred million years or less [Oberbeck and Fogleman, 1989].

3. Nature of the Microbial Fossil Record

The microbial fossil record consists of a wide variety of information, including morphological fossils (e.g., preserved cellular remains, biofabrics, and stromatolites [Walter, 1994; Simonson and Carney, 1999] and chemofossils (e.g., biominerals and organic biomarker compounds [Summons and Walter, 1990; Summons et al., 1996]) and associated isotopic or other geochemical signatures [Schidlowski et al., 1983; Des Marais, 1997]. In light of the previous discussion, it is noteworthy that microbial biofabrics and mesoscale biolaminated sedimentary structures (e.g., stromatolites) can persist in rocks even after biochemical signatures have been lost through catagenesis (molecular breakdown at high temperatures). Similarly, minerals may retain isotopic or trace element signatures indicative of life even after primary organic materials have been degraded and lost.

More than 99% of the organic carbon fixed by organisms is recycled before it can enter the sedimentary record [Holland, 1984]. Still, the most abundant fossil evidence for life on Earth is the enormous reservoir of reduced (organic) carbon preserved in sedimentary and metamorphic rocks. Following burial, early diagenetic mineralization, promoted by anoxia, often enhances the preservation of organic materials by slowing the processes of microbial degradation [Allison and Briggs, 1991a]. Although the amount of biogenically fixed carbon retained in the crust at any given time is very small, when integrated over time, the total proportion of the crustal carbon reservoir (and the fossil record contained therein) is immense [Des Marais, 1997]. The small amount of carbon that escapes degradation does so mostly by virtue of being rapidly incorporated into fine-grained, low-permeability sediments or chemical precipitates.

4. Processes of Microbial Fossilization

Studies of fossilization processes in modern environments indicate that the preservation of fossil information is controlled by the physical, chemical, and biological conditions acting during sedimentation and early diagenesis (the post-depositional events that affect a sedimentary rock). Sedimentary processes may be divided into two broad categories: (1) detrital systems, in which rock materials are fragmented by processes of physical and chemical weathering and are transported as discrete grains to sites of deposition where they accumulate as layered sediments, and (2) chemical systems, where the dissolved materials derived from chemical weathering are precipitated at a depositional site through inorganic and/or biological processes. In most cases, the two processes operate together to produce the sedimentary record. The following sections identify some of the factors that affect fossilization processes within these sedimentary systems.

4.1. Fine-Grained Detrital Systems

With burial, the permeability of fine-grained, clay-rich detrital sediments decreases rapidly owing to compaction (>85% volume reduction). In addition to the reduction of permeability, clays may also play an important role in the preservation of biosignatures by binding organic molecules to charged mineral surfaces or incorporating them into clay structures as interlayer cations. For example, during burial diagenesis, biogenic signatures such as organogenic methane may be preserved at interlayer cation sites in clays long after other volatile constituents

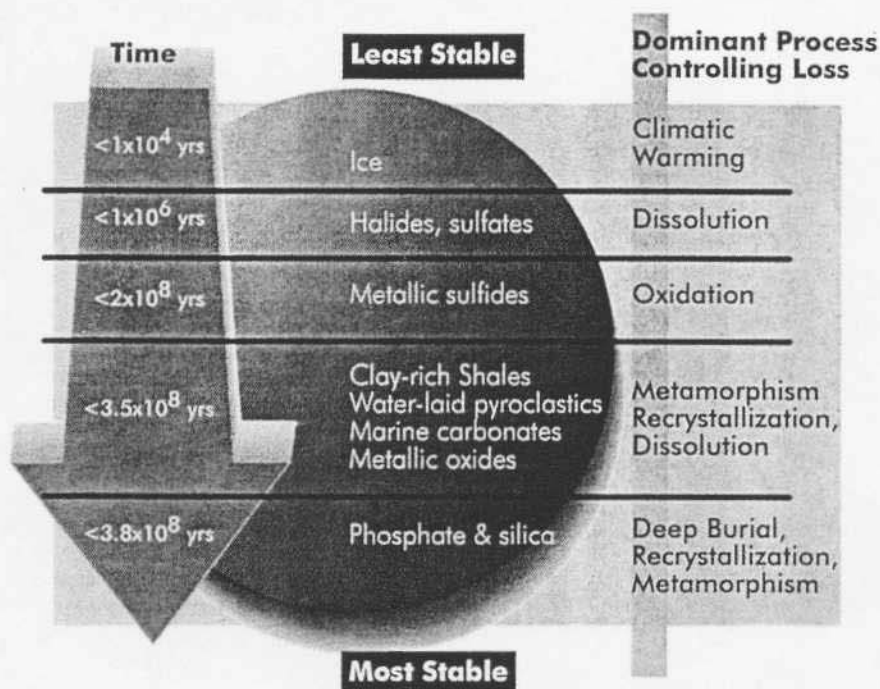


Figure 1. The estimated crustal residence times of common sedimentary minerals important in preserving a microbial fossil record on Earth. Crustal residence times are maximum estimates based on the occurrences in the geologic record.

have migrated out of a host rock [see *Compton et al.*, 1992]. Clays have even been shown to absorb small organisms (microphages), thereby enhancing their long-term survival [Moll and Vestal, 1992].

Organic materials are normally degraded to stable end products during early diagenesis [see *Summons et al.*, 1996]. In addition to early compaction, another key to preservation in these environments is early diagenetic mineralization, a process promoted by anoxia [Allison and Briggs, 1991a]. Although the degradation of organic materials is often assumed to be slower under anaerobic conditions, the situation is actually quite complex and depends on a variety of factors, including temperature and the composition and structure of the organics [Heinrichs and Reeburgh, 1987]. Allison [1988b] showed through mass balance calculations that anaerobic sulfate reduction is capable of degrading twice as much organic matter as aerobic decomposition. Nevertheless, there are many well-documented Phanerozoic examples of soft-bodied organisms preserved in fine-grained detrital sediments and water-lain volcanic ash deposits [see Allison and Briggs, 1991a, Table 4]. Preservation as organic-walled fossils is a common mode in fine-grained Precambrian sediments [e.g., Hofmann, 1971; Walter *et al.*, 1990]. Such examples demonstrate the ability of such deposits to protect organic materials from oxidation over time spans of billions of years.

In fine-grained detrital systems, morphofossils are usually preserved along bedding planes as two-dimensional compressions. However, three-dimensional preservation may occur in shales where early diagenetic mineralization forms concretionary nodules within the host rock. Berner [1968] showed that concretions form within microenvironments produced through organic matter degradation. This degradation is often an incomplete process, however, as the core regions of many concretions often contain concentrations of well-preserved organic

matter, suggesting that early mineralization was able to arrest degradation by decreasing permeability and creating a closed chemical environment [see Allison and Pye, 1994].

4.2. Entombment by Chemical Precipitates

Microbial fossilization may also occur when organisms and/or their by-products are entombed within mineral precipitates like silica, phosphate, carbonate, and metallic oxides and sulfides. Chemical sediments include primary precipitates as well as authigenic cements that permineralize (infuse) and/or replace inorganic sedimentary frameworks and microbial fossils during early diagenesis.

Quartz, the stable form of silica at the Earth's surface, has a prolonged residence time in the crust (Figure 1). Not surprisingly, excellent preservation is often observed in cherts, silica-rich sedimentary rocks formed either by the precipitation of primary silica or by the replacement of preexisting host sediments by silica during early diagenesis [Schopf and Walter, 1983].

The most widespread chemical precipitates during the Precambrian were marine carbonates deposited on shallow continental platforms [Grotzinger, 1994]. However, carbonates tend to undergo pervasive recrystallization during diagenesis, resulting in substantial losses of primary microfabric and fossil information. Exceptions include cases where framework carbonate and organic materials were replaced by secondary silica or phosphate before significant degradation of organic matter. This process is illustrated by carbonates of the Belcher Island Group of the Canadian Arctic [Hofmann, 1976], which contain well-preserved fossil remains of microbial mats dominated by the cyanobacterium *Eoentophysalis* (Figure 2). In this example, cellular microfossils were preserved in both primary carbonate and secondary (early diagenetic) silica. While carbonate layers retain wispy laminae of degraded organic materials and occa-



Figure 2. Thin section photomicrograph showing fossilized cyanobacterial mats dominated by the form genus, *Eoentophysalis*. Cellular remains were best preserved where entombed by early diagenetic silica (see arrow). In areas of primary carbonate, preservation is generally poor, consisting mostly of undifferentiated aggregates of organic matter. Belcher Island Group (2.1 Ga), Canada. Loan of thin section courtesy of H. Hofmann, University of Montreal. Base of photo is ~ 0.1 mm wide.

sional "ghosts" of cellular forms, microbiotas preserved in silicified laminae retain many cellular forms and higher-order mat features. Clearly, compared to carbonate, the fidelity of morphological preservation is superior in fine-grained silica.

Because of its stable crystalline structure and resistance to recrystallization, sedimentary phosphate is also an excellent host mineral for the long-term preservation of organic materials. Phosphatization is favored in modern anoxic environments, where microbes mediate the mineralization of organic phosphate. Changes in the pH of microenvironments during sulfate reduction can induce the localized precipitation of apatite in association with decaying organic matter. During this process, microorganisms and recalcitrant organic materials may be preserved by replacement. Although the phosphatization of organic materials is uncommon in modern environments, there are well-documented examples in the fossil record [Lucas and Prevot, 1991]. Examples of cellular-level preservation were discussed by Xiao *et al.* [1998] for Late Neoproterozoic phosphorites of China, and Mojzsis *et al.* [1996] reported chemofossil evidence in phosphates from ~ 3.87 Ga metasedi-

mentary sequences at Akilia Island, Greenland. The Akilia Island rocks comprise the oldest known marine sequences on Earth [Nutman *et al.*, 1997]. Graphite preserved in sedimentary phosphate grains in these metasediments exhibits light carbon isotope ratios suggestive of biological fractionation. Mojzsis and Arrhenius [1998] argued for sedimentary phosphates as target minerals in the search for a Martian fossil record.

5. Destructive Processes: Diagenesis, Burial, and Metamorphism

With increasing burial depth, a host rock is subjected to progressively higher temperatures and pressures which markedly alter and eventually destroy primary biogenic signatures. With burial to temperatures above $\sim 80^\circ\text{C}$, the complex organic compounds in sediments begin to undergo catalysis (thermal cracking). This process liberates the most volatile constituents of organic compounds forming petroleum and natural gas. These hydrocarbons typically migrate out of the source rock along density gradients, eventually accumulating along permeability barriers at higher stratigraphic levels in the crust. The lighter distillates formed during catagenesis usually migrate completely out of the host rock, leaving behind only refractory components known as kerogen. These residual organic materials may retain primary biogeochemical information in the form of biomarker compounds and isotopic signatures indicative of biology [Brocks *et al.*, 1999].

With increasing burial, kerogen continues to undergo progressive losses of volatile components, becoming enriched in long-chained, heavily cross-linked polymers. This maturation process is accompanied by predictable changes in the color and opacity of kerogen. The isotopic composition of kerogen also changes in a predictable way during diagenesis. The degree of alteration (and accompanying losses of biological information) can be assessed, and, to some extent, corrected for, by determining the H/C ratio of the kerogen which is related to the thermal history [Des Marais, 1997]. However, once burial temperatures exceed the $\sim 150^\circ\text{--}200^\circ\text{C}$ required for low-grade metamorphism, chemofossil evidence becomes more difficult to interpret or is lost completely.

6. Present Martian Surface Environment

More than 20 years ago the Viking landers conducted biology experiments at two sites on the Northern Plains of Mars [Klein, 1992, 1998]. These experiments were designed to search for extant life within Martian soils. It was assumed that if life was present, it could be most easily discovered by detecting the by-products of metabolism. Adding water and nutrients to Martian soil samples was expected to stimulate growth, producing volatile products that could be detected using Gas Chromatography-Mass Spectrometry (GCMS). The metabolic model, which dominated the strategy for Viking exobiology, provided a narrow yet powerful focus for exploration. However, after nearly two decades of analysis, the results of the Viking biology experiments have been widely accepted as indicating an absence of extant life, at least within surface soils [Klein, 1992, 1998]. Liquid water is regarded as essential for metabolic activity in living systems. However, it is presently unstable at the surface of Mars owing to the low atmospheric density (~ 7.5 mbar at 2.0 km elevation) and mostly subfreezing temperatures (daily temperature range at the equator: 180°K to 280°K , and 150°K at high latitudes in winter [Carr, 1996].

The extremely low water activities within surface environments on Mars comprise a formidable barrier to life [Horowitz, 1979; Klein, 1992]. In addition, the thin, CO₂-rich atmosphere lacks molecular oxygen, and there is therefore no ozone layer to protect the surface from ultraviolet radiation [Clark, 1998; Kuhn and Atreya, 1979]. On Earth, many microorganisms are known to survive in high-UV environments by living within rocks as endoliths [Golubic et al., 1981] or by producing UV-absorbing pigments (e.g., carotenoids) which act as sunscreens [Garcia-Pichel and Castenholz, 1991]. However, today the Martian surface experiences a UV flux several times that considered lethal to terrestrial organisms, and it is problematic whether biological systems could have adapted to such conditions.

As on Earth, organic compounds have been continuously delivered to the Martian surface throughout its history in association with interplanetary dust particles (IDPs), meteorites, and cometary impacts [see Chyba and Sagan, 1992]. However, the Viking lander GCMS failed to detect any organic compounds in the Martian regolith at sensitivities of 1.0 ppb [Klein, 1992]. The absence of organics in the Martian regolith has been attributed to highly reactive oxidants, such as peroxides or "superoxides," that would rapidly destroy any organic compounds present.

Viking sampled a very limited range of materials mostly consisting of fine, wind-transported components of the regolith. By terrestrial standards, such materials are regarded as unsuitable for the long-term preservation of fossil biosignatures. However, fossils could still be preserved within the interiors of well-indurated (low-permeability) sedimentary rocks at the Martian surface. This is certainly the case for the highly oxidizing surface environment of the Earth, where ancient organic materials have survived within the interiors of rocks for billions of years. It is notable in this context that even where all the organic materials have been oxidized and removed from a rock, fossil evidence may still be preserved in the form of diagnostic biofabrics and/or isotopic signatures. Thus any in situ assessment of biogenicity will need to consider the broad spectrum of potential fossil evidence discussed earlier.

7. Ancient Martian Surface Environments

Given the possibility that liquid water and an inventory of complex organic compounds existed in the early Martian crust [Chang, 1995; Shock and Shulte, 1998], life could have originated and flourished in surface environments up until the time the planet lost its atmosphere [McKay and Stoker, 1989]. This period is likely to have lasted several million years, overlapping the time in which life originated on the Earth. Furthermore, impact modeling of early Mars suggests that it would have been a more favorable place for the survival of life from the standpoint of late, giant impact hazards [see Sleep and Zahnle, 1998]. The following discussion seeks to identify some important habitats on Mars where life may have flourished during the early history of the planet.

In contrast to the inhospitable nature of the Martian surface encountered by the Viking landers, images obtained from orbit presented a remarkably different picture of the early history of the planet. In particular, the heavily cratered southern highlands of Mars showed numerous small valley networks (Figures 3b and 3c) resembling terrestrial valleys carved by running water [Masursky, 1973; Carr, 1987, 1996; Squyres, 1989]. These ancient features were attributed to a wide range of surface erosion processes, including atmospheric precipitation and

surface runoff [Mars Channel Working Group, 1983], subsurface sapping [Sharp and Malin, 1975; Pieri, 1980], and, at higher latitudes, the erosive action of ice-rich debris flows [Squyres, 1978; Lucchitta, 1984]. In some instances, valleys were observed to terminate along the margins of flat-floored basins that could have once held lakes [Goldspiel and Squyres, 1991] (Figures 3c and 3d). Although the duration of hydrological conditions responsible for the formation of the small valley networks remains uncertain, within some dendritic systems, higher-order tributaries, as well as terraced channels and basin margins, suggest that surface hydrologic activity could have persisted for prolonged periods of time.

Near the end of heavy bombardment (~3.8 billion years ago), the planet began to lose its atmosphere. The decline in atmospheric density appears to have progressed rapidly through losses to space, crustal weathering, and the aqueous precipitation of carbonates and evaporites [Jakosky, 1991]. Model-based calculations suggest that loss of the atmosphere could have occurred in <500 million years [Schaefer, 1993]. Hydrothermal systems may have been an effective means for sequestering atmospheric CO₂ as carbonates in the crust [Griffeth and Shock, 1995]. At the beginning of late bombardment, Mars may have passed through a transitional period dominated by ice-covered lakes and streams [McKay and Davis, 1991]. From an exploration standpoint, the sedimentary deposits left behind as surface hydrological systems disappeared may represent the most accessible storehouses of information for reconstructing the early volatile and climate history of the planet. Such deposits are also primary targets for exopaleontology.

8. The Martian Subsurface

Subsurface aqueous systems could have provided clement environments for life on Mars long after the planet lost its atmosphere and surface water [see Clifford, 1993]. This observation profoundly influences our approach to the exopaleontological exploration of Mars, particularly if it can be shown that atmospheric precipitation and surface runoff were limited during early Martian history. On Earth, the shallow crust comprises a vast, virtually unexplored aqueous realm that is home for a diverse range of microbial species, lifestyles, and metabolic strategies [Pedersen, 1993; Fredrickson and Onstott, 1996; Stevens, 1997]. This suggests the possibility that the Martian subsurface is similarly populated by a variety of chemotrophic microorganisms [Boston et al., 1992; Gold, 1992], including chemolithoautotrophic forms that require no organic input from the surface [Stevens and McKinley, 1996].

During late bombardment, another class of channels was formed through catastrophic outflows of subsurface water [Baker and Milton, 1974; Baker, 1982]. Some of these features (such as Dao Vallis) formed on the flanks of volcanoes in the ancient highland terrains of Mars [Crown et al., 1992; Squyres et al., 1987] (Figure 3a). However, most outflow channels formed along the southern margins of the Northern Plains of Mars. The largest outflows debouched onto Chryse Planitia (Figure 4a), located east of the Tharsis [Carr, 1981]. Many of the channels in this region originated within chaotic terrains where the surface collapsed during and following outflooding (Figure 4b), presumably because of melting of the underlying cryosphere [Masursky, 1973]. The flows responsible for carving these channels were capable of transporting and depositing huge volumes of sediment [Baker, 1982; Baker et al., 1993; Komar, 1979, 1980]. In the case of the channels that debouched

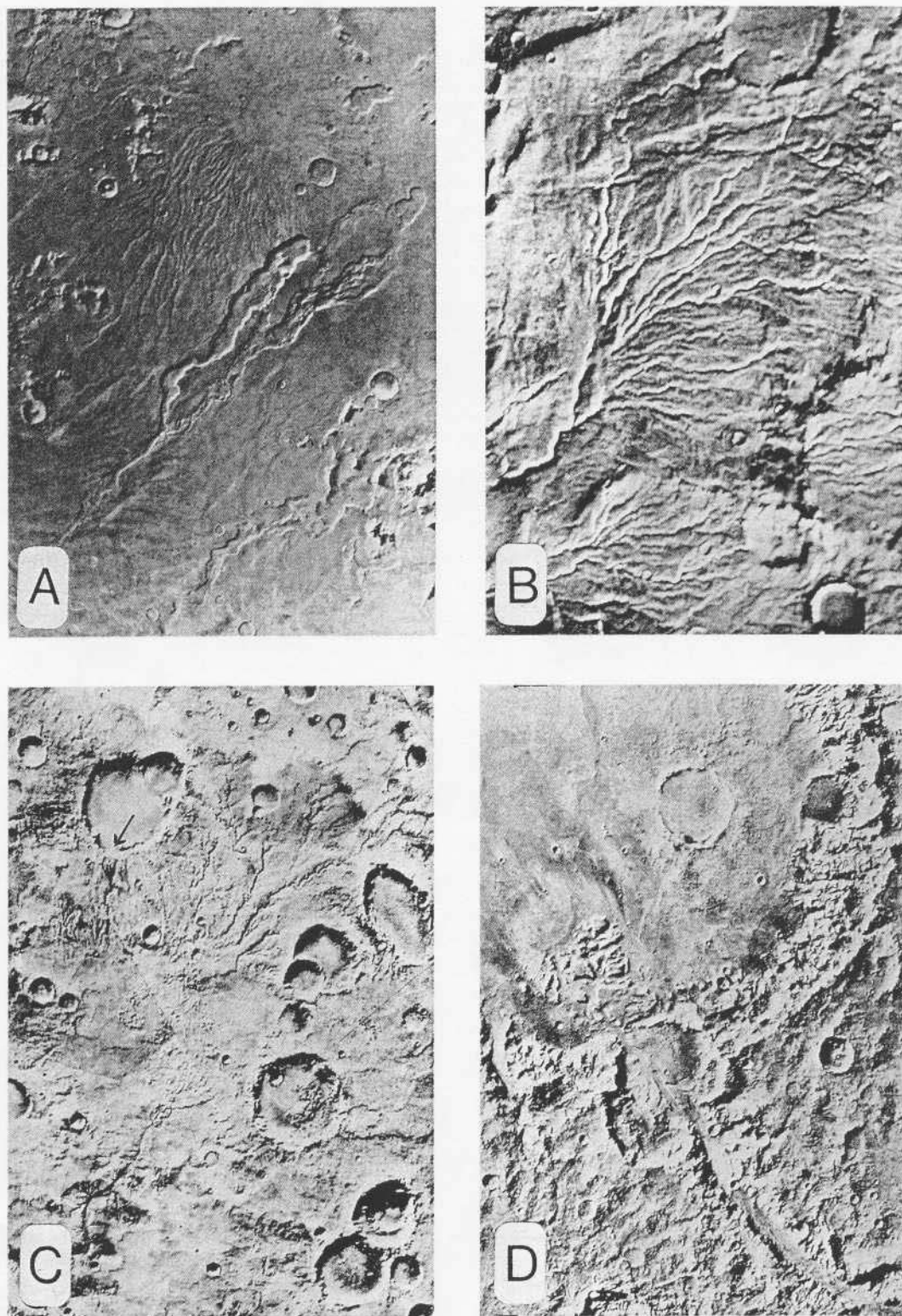


Figure 3. Water-carved geomorphic features on Mars: (a) Hadriaca Patera, an ancient Martian volcano located in the southern highlands of Mars, shows a large outflow channel that is thought to have been formed by the melting of ground ice by subsurface heating, possibly by igneous intrusives (photo courtesy of NASA). (b) Small valley networks in the Thaumasia Fossae region of Mars were formed by surface runoff or sapping flow (photo courtesy of NASA). (c) Small valley networks of the Parana Vallis system terminate at the margins of a possible paleolake basin; some of the small valleys (arrow) originate at the edge of impact basins and may have been fed by hydrothermal outflows (photo courtesy of NASA). (d) Gusev Crater (~150 km impact crater) was a terminal basin for water that carved Ma'adim Vallis, an 800 km long channel that originates to the south; this crater basin may have been the site of an ancient paleolake system (see text).

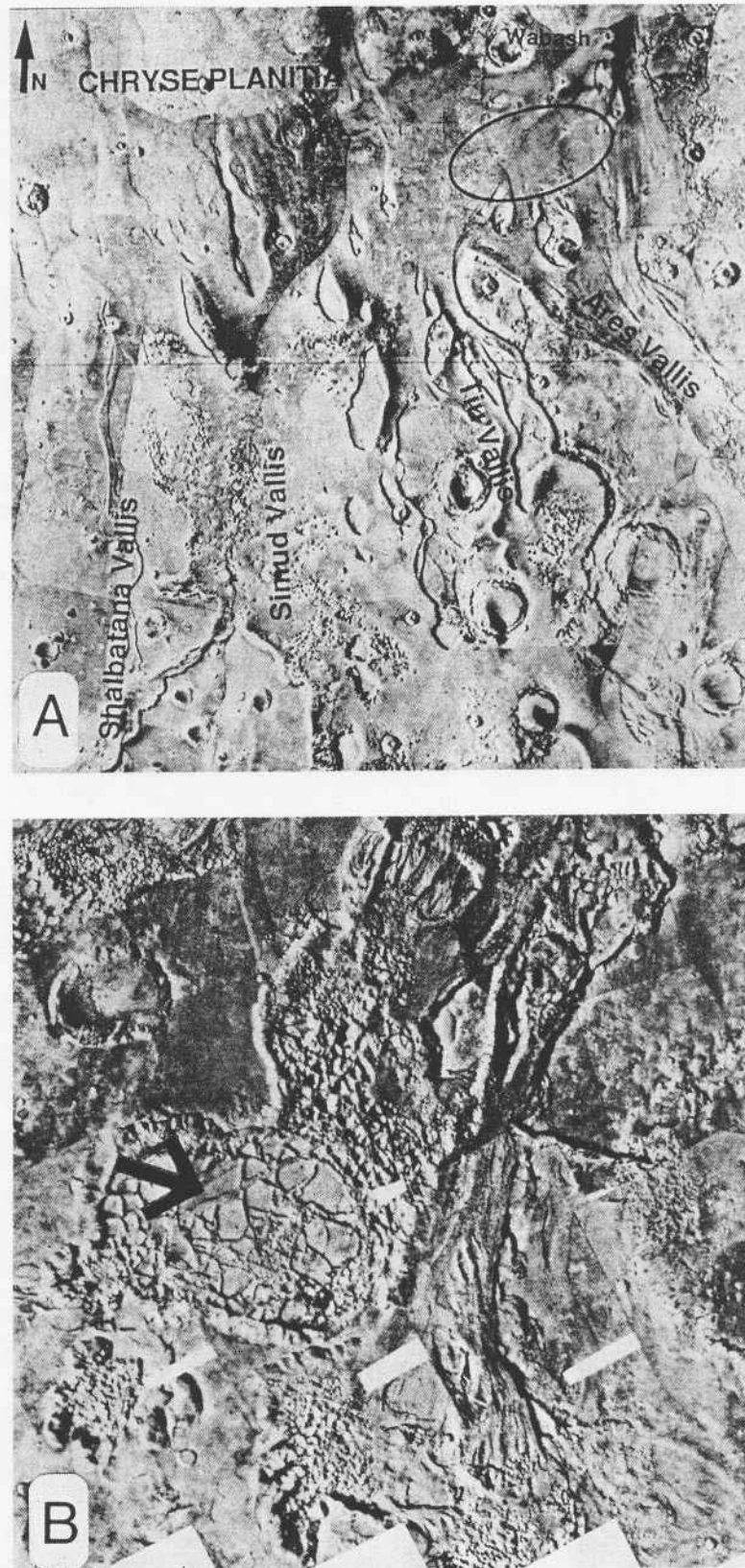


Figure 4. Site selection for the Pathfinder Mission. In Figure 4a, the Ares and Tui Valles outflow channel systems show large-scale erosional features created during catastrophic outflows of water from the subsurface. The landing site for the Pathfinder mission is shown by the ~ 150 km error ellipse located at the mouth of Ares Vallis. Photomosaic is courtesy of Jet Propulsion Laboratory. Figure 4b shows chaotic (collapsed) terrains that were the source of the outflows that created the outflow channels in Figure 4a. Hydaspis chaos (arrow) is a semicircular collapsed area (~ 60 km diameter) that may have formed above a focused heat source (e.g., an igneous intrusion).

on the Northern Plains, most of the sedimentary load was probably derived from the ancient highland terrains further south. The Pathfinder landing site was positioned at the mouth of one of these channels (Ares Vallis). In situ analysis of the landing site supported the presence of fluvial deposits, modified by later aeolian and impact processes [Golombek *et al.*, 1997b].

9. Site Selection for Mars Exopaleontology

The lack of crustal recycling probably doomed any possibility for sustained surface life on Mars. However, long-term stability of the Martian crust is likely to have preserved an extraordinary record of the early history of the planet. On the basis of crater counts, extensive areas of the southern highlands of Mars are estimated to be older than 3.8 billion years [Carr, 1996]. This is consistent with the ancient age (~ 4.56 Ga) of Martian meteorite ALH 84001 [McKay *et al.*, 1996], which is believed to have been ejected from a site in the southern highlands [Barlow, 1997]. Although there may have been extensive impact metamorphism, these ancient rock sequences are unlikely to have been deeply buried or metamorphosed. In addition, because surface water disappeared early in the planet's history, the effects of long-term aqueous weathering may have been minimal. This is supported by evidence for limited aqueous alteration in SNC meteorites which were derived from Mars [McSween, 1994]. The following discussion specifies several types of ancient geological environments which hold special interest for Mars exopaleontology.

10. Surface Hydrothermal Systems

Hydrothermal systems have been targeted as important environments for studies of early biosphere evolution on the primitive Earth [Farmer, 1998; Bock and Goode, 1996]. The higher heat flow, widespread volcanism, and likelihood of giant impacts during the early Archean [Sleep *et al.*, 1989] support the view that hydrothermal systems were widespread during the time Earth's biosphere first emerged. Hydrothermal processes also appear to have also played an important role in the early history of Mars [Farmer, 1996]. From the standpoint of early impact hazards, Mars is likely to have been a safer environment than the Earth for originating and sustaining an early biosphere [Sleep and Zahnle, 1998]. The importance of hydrothermal deposits as potential targets for Mars exopaleontology was heightened by the ongoing controversy over the biogenicity of features preserved in what are generally regarded to be hydrothermal carbonates in Martian meteorite ALH 84001 [McKay *et al.*, 1996]. Hydrothermal deposits have been assigned a high priority in the exploration for a Martian fossil record [Walter and Des Marais, 1993; Farmer and Des Marais, 1994a; Walter, 1996].

In developing a strategy to explore for ancient hydrothermal deposits on Mars, it is useful to consider the methods developed by explorationists who explore for economic mineral deposits on the Earth [Huntington, 1996; Horn, 1996]. Because of their characteristic mineralogy, hydrothermal deposits may often be detected using high-resolution remote-sensing methods [Goetz *et al.*, 1983, 1985; Kruse *et al.*, 1990]. Common hydrothermal mineral assemblages include silica, carbonate, and various metallic oxides and sulfides, as well as diagnostic silicate minerals, including clays formed by the hydrothermal alteration of country rocks [Kruse *et al.*, 1990]. Shallow epithermal

mineral assemblages typically show distinctive zonation patterns around vents that reflect the typically steep gradients in temperature, pH, and aqueous geochemistry. Epithermal ore deposits have also been identified using airborne magnetometers by spotting zones of demagnetization produced by hydrothermal heating [Goetz *et al.*, 1983].

10.1. Subaerial Thermal Springs

In subaerial thermal springs, microbial species are arrayed along thermal gradients according to their temperature tolerances, creating characteristic biomes that are easily discerned by variations in mat pigmentation and structure (Plate 1a). Springs deliver nutrients and reduced compounds to the surface environment that are capable of sustaining high rates of biological productivity. Microbial communities flourish in these extreme environments owing to the exclusion of species that would normally compete with, or graze upon, the microbial mats and biofilms present.

The rapid outgassing and temperature decline along thermal outflows frequently drives the rapid and pervasive precipitation of minerals, which entombs many microorganisms (Plate 1b). As a result, hydrothermal deposits usually contain a wide variety of microbial fossil information, including mineral replacements, external molds of cells and filaments, biofabrics, and stromatolites [Walter *et al.*, 1972; Walter and Des Marais, 1993; Farmer and Des Marais, 1994b; Farmer *et al.*, 1995c; Cady and Farmer, 1996; Trewin, 1996; Jones *et al.*, 1997; Jones and Renault, 1997].

Studies of modern subaerial springs in Yellowstone have shown that fossilization occurs almost entirely by the encrustation of exterior walls of cells and/or sheaths, followed by the rapid degradation of organic materials [Farmer and Des Marais, 1994b; Cady and Farmer, 1996]. From a paleontological perspective, the most important organisms in modern subaerial thermal springs are larger mat-forming filamentous species (primarily cyanobacteria) that occur at temperatures below 73°C. Phototaxis of these organisms often produces mat structures that account for most of the mesoscale fabrics observed in ancient thermal spring sinters. In these systems, fossil information is captured at scales ranging from the individual organism up to composite (community-level) biofabrics and stromatolites. Although the cyanobacterial contributions to sinter fabric dominate over most of the system, biofilms of micron-sized filamentous Archaea also contribute importantly to the structure and morphogenesis of stromatolites formed near vents and in the shallow subsurface, where temperatures exceed the upper limit for cyanobacteria [Cady and Farmer, 1996].

Sinter deposits are initially very porous and subject to extensive infilling and cementation during diagenesis. In addition, primary minerals are typically metastable phases that undergo extensive recrystallization to form stable polymorphs during diagenesis (e.g., opaline silica to quartz, aragonite to calcite, amorphous iron oxide to hematite). Studies of ancient siliceous sinter deposits suggest that much of the microscale information is lost during diagenetic recrystallization. In a well-studied Devonian (~ 350 million year old) example from NE Australia, the microbial fossil record is dominated by mesoscale stromatolitic fabrics and microscale composite biofabrics (palisades and shrubs) typical of lower-temperature microenvironments [see Walter *et al.*, 1996, 1998].

On Earth, subaerial hydrothermal springs are common features of continental volcanic settings [Henley, 1996; Walter, 1996]. Photogeologic evidence indicates that volcanic terrains

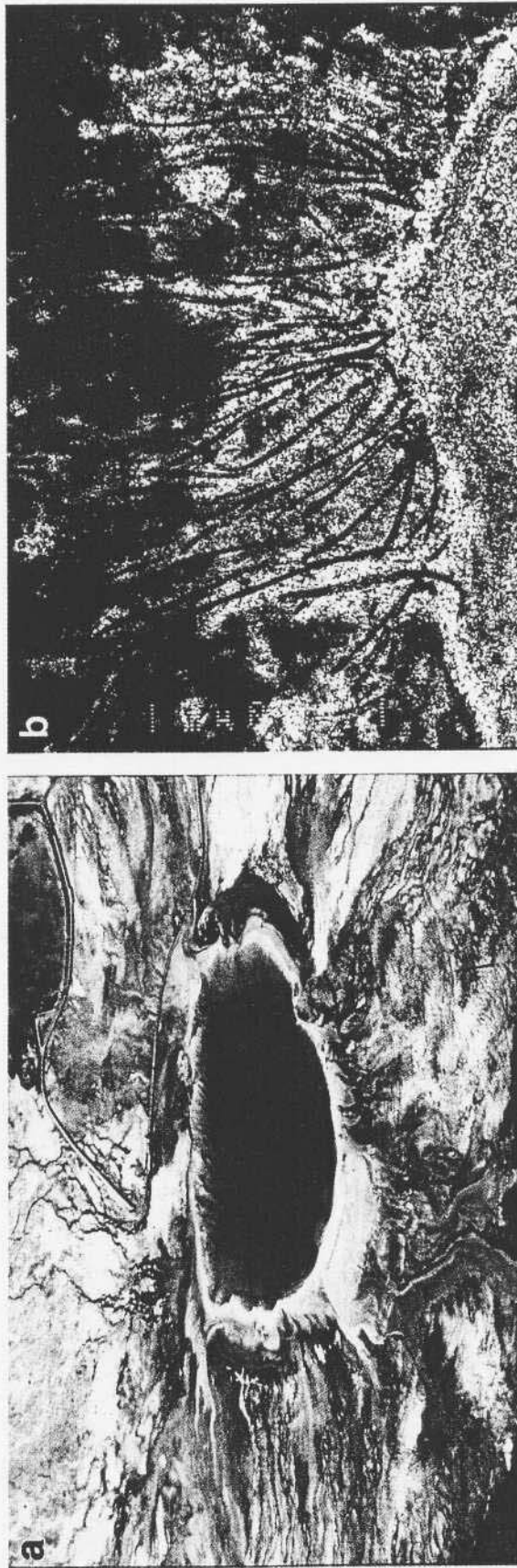


Plate 1. Fossilization processes in subaerial thermal springs. Plate 1a is an aerial view of Grand Prismatic Spring, Lower Geyser Basin, Yellowstone. Variations in color along outflows reflect different cyanobacterial communities. White areas are opaline silica deposited as outflow channels were abandoned. Siliceous sinters in these areas contain abundant microfossils. Note boardwalk for scale. In Plate 1b, vertically growing *Calothrix* sp. show encrustation of exopolymer sheaths (dark tubes) by opaline silica (white material). Scale bar is 10 microns.

are widespread on Mars [Carr, 1981]. Outflow channels associated with potential heat sources, such as impact craters [Brakenridge *et al.*, 1985; Newsom, 1980] (Figure 3c, arrow), volcanic cones [Crown *et al.*, 1992] (Figure 3a), or chaotic terrains (collapsed ground thought to have formed by the melting of ground ice (Figure 4b) [Farmer *et al.*, 1995a], suggest that there are many potential sites for ancient hydrothermal deposits on Mars [Farmer, 1996]. Depending on the temperature, pH, Eh, and the composition of basement rocks, thermal springs deposit simple, often monomineralic precipitates of silica, calcium carbonate, or metallic oxides or sulfides [Henley, 1996]. Such deposits may be detectable from Mars orbit using high-resolution infrared mapping techniques.

10.2. Subaqueous Thermal Springs

On Earth, most hydrothermal systems are associated with lithospheric plate margins, either on the deep sea floor along mid-ocean ridges (divergent margins) or within accretionary wedges of arc-trench settings (convergent margins [Tivey, 1995]. To date there have been few published reports of microbial fossil assemblages associated with subaqueous deep-sea vent deposits [Zierenberg and Schiffman, 1990; Cook and Stakes, 1995; Walter, 1996]. However, documented examples suggest that modes of preservation are comparable to those observed in subaerial systems in terms of mode (encrustation, infilling, and/or mineral replacement) and predominant scale of preservation (primarily, biofabrics and higher-order stromatolitic fabrics).

Caldera floor deposits have long been regarded as important targets for economic ore deposits on Earth [Henley, 1996]. Subaqueous thermal springs and associated microbial mats have been reported from the floors of some volcanic crater lakes [Dymond *et al.*, 1989], and heavily mineralized crater and caldera floors (such as Yellowstone) appear to provide excellent environments for microbial fossilization. However, the microbial paleontology of such environments is still largely unknown [Lockley and Rice, 1990]. Well-preserved fossil assemblages, including microbial biofabrics and stromatolites, have been described from silicified volcanic lake deposits in the Carboniferous of Scotland [Rolfe *et al.*, 1990], suggesting the potential importance of these environments as repositories of microbial fossil information.

11. Subsurface Hydrological Systems

The fossil record of subsurface environments on Earth is presently poorly known. However, filamentous microstructures of putative biological origin have been described from a variety of low-temperature (<100°C) hydrothermal deposits (mostly vein, vug, and vesicle-fills in volcanic rocks) [Kretzschmar, 1982; Hofmann and Farmer, 1997; B. A. Hofmann and J. D. Farmer, manuscript in preparation, 1999]. Although direct access to such environments on Mars is not within the reach of the currently planned robotic missions, excavation by impact has undoubtedly uncovered a wide variety of subsurface materials as ejecta. In addition, some of the steep-walled canyons on Mars (e.g., Vallis Marineris and associated chasmata) expose crustal sections to depths of several kilometers, and it is possible that fossiliferous materials have been supplied to talus slopes and/or debris flows shed from canyon walls. Lastly, the catastrophic flows that carved the large outflow channels described earlier could have brought such materials to the surface, depositing them on channel floors or on deltas formed where streams entered lakes.

12. Paleolake Basins

Using Viking orbital data, many putative paleolake basins (inclusive of impact craters and volcanic calderas) have been identified within the Martian highlands (Figures 3c and 3d) [Goldspiel and Squyres, 1991; Scott *et al.*, 1991; Scott and Chapman, 1991; Chapman, 1994; Landheim *et al.*, 1994; Farmer *et al.*, 1995b; Grin and Cabrol, 1997]. In contrast to hydrothermal deposits, which are often disseminated or otherwise spatially restricted, paleolake beds may offer the largest and most easily identified targets from orbit for future landed missions. Terminal lake basins (i.e., those formed where water leaves only by evaporation) are especially important targets for exopaleontology because on Earth such environments tend to exhibit both high rates of microbial productivity (which generates an abundance of organic-rich detrital sediment) and chemical sedimentation (which tends to capture and preserve microbial remains). During lake lowstands, when salinities and pH tend to be high, the precipitation of carbonates and a variety of evaporite minerals is particularly favored.

12.1. Lacustrine Spring Carbonates (Tufas)

Carbonate deposits form around spring vents on the floors of alkaline lakes where calcium-rich artesian springs undergo mixing with bicarbonate-rich alkaline spring water. Such low temperature carbonate deposits are broadly referred to as "tufa" [Scholl and Taft, 1964; Council and Bennett, 1993]. Examples of spring-deposited tufas include the carbonate pinnacles at Mono Lake, eastern California (Figures 5a and 5b), and at Pyramid Lake in northern Nevada [Benson, 1994]. Because carbonate precipitation is driven by the mixing of lake and ground waters of differing chemistry, tufa towers grow only while vents remain submerged. However, along the shallow margins of alkaline lakes, solar heating, evaporation, and wave turbulence can result in outgassing of CO₂, which locally increases pH, causing the widespread precipitation of carbonate crusts and cements. In addition to inorganically precipitated tufas, such environments may also harbor finely laminated carbonates resembling stromatolites (e.g., Figure 6a). Regardless of the processes (inorganic or biological) driving carbonate precipitation, where microorganisms are present, they are frequently entombed and fossilized. In addition to primary biofabric information, stromatolitic tufas frequently contain organic-walled microfossils and particulate kerogen (Figure 6b).

12.2. Lacustrine Shales and Marls

The preservation of organic-walled microfossils and biomolecular compounds is most commonly observed in association with low-temperature, anaerobic sedimentary systems where early diagenetic mineralization is pervasive [Allison, 1988a; Allison and Briggs, 1991a, b]. Shales and marls deposited under such conditions are typically enriched in organic carbon, becoming source rocks for the generation of petroleum. Phanerozoic shales (e.g., Messel, Hunsrück, and Burgess), marls (e.g., Solenhofen Limestone), and water-lain volcanic ash deposits (e.g., John Day Formation) provide some of our best examples of soft-bodied fossil assemblages [Allison and Briggs, 1991a, Table 4, p. 44; Allison and Briggs, 1991b]. In addition, organically preserved body fossils of microorganisms and macroalgae are also common in Precambrian shales [e.g., Towe *et al.*, 1992; Mendelson *et al.*, 1992]. Such examples reveal the potential importance of fine-grained detrital sediments as targets for organically preserved fossils on Mars.

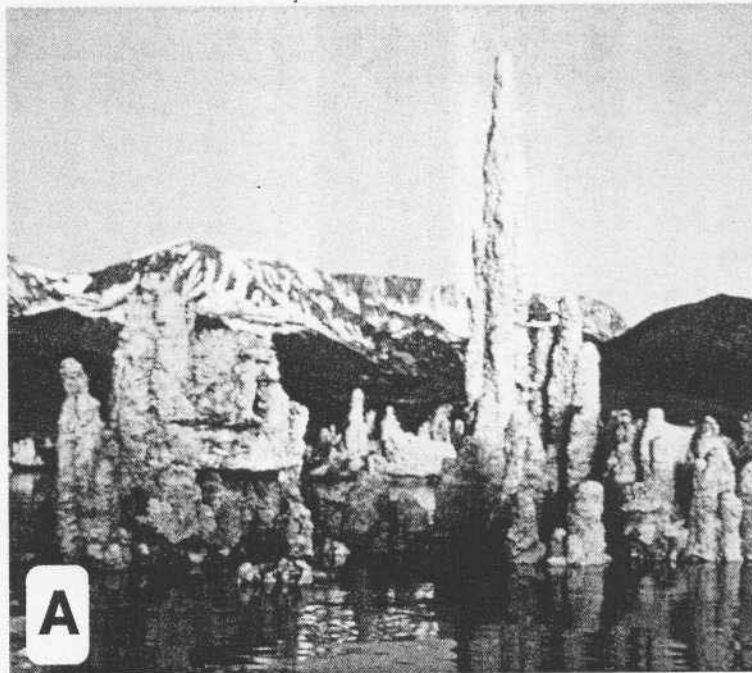


Figure 5. Alkaline lake tufas. Figure 5a shows pinnacle-shaped tufa towers located at South Tufa Reserve, Mono Lake, California. The tallest towers are ~6 m high. Figure 5b is a high-altitude oblique aerial photo of the Mono Basin, a terminal lake basin in eastern California. Note the positions of ancient shorelines left behind with the retreat of Pleistocene Lake Russell. (Photo is courtesy of the Mono Lake Committee.)

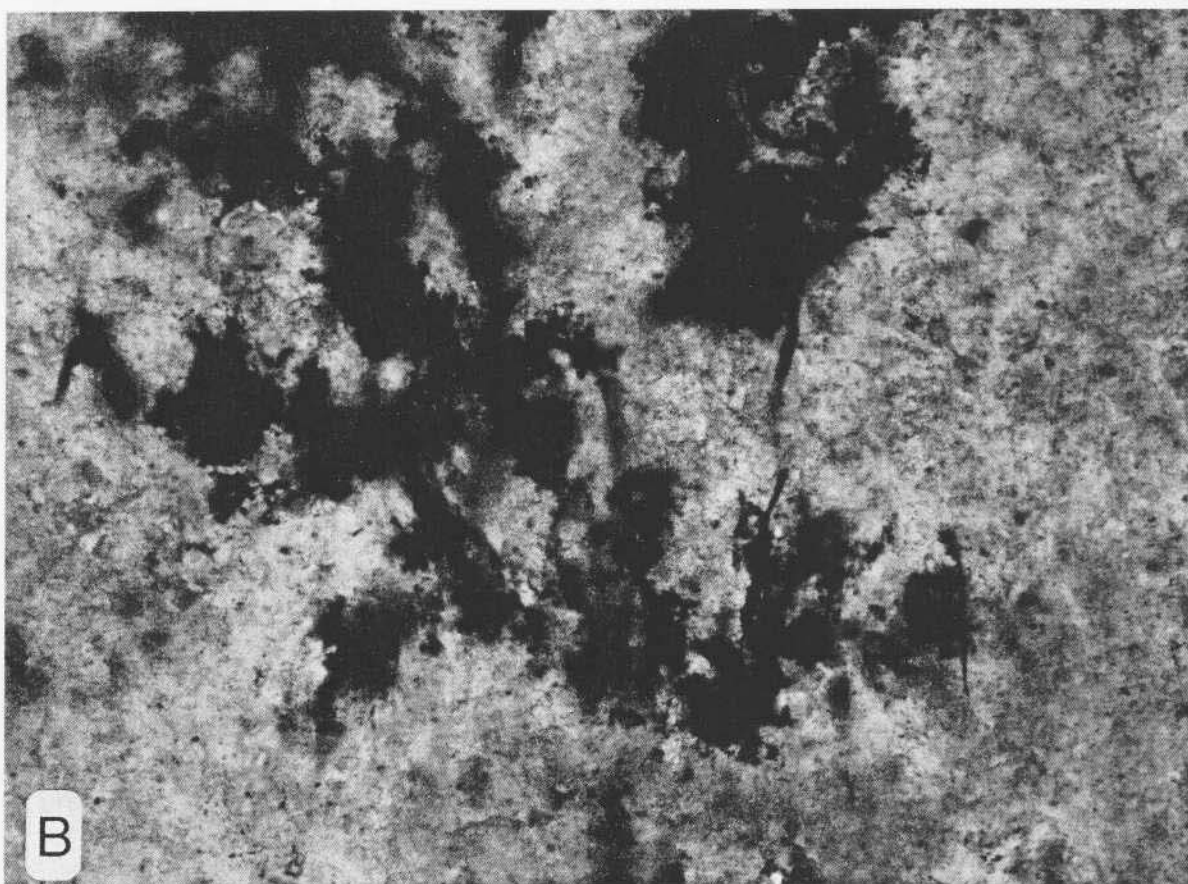


Figure 6. Paleontology of tufas. Figure 6a shows stromatolitic tufa from a large tufa dome located at Pyramid Lake, Nevada. Figure 6b shows organic-walled, filamentous microfossils preserved in stromatolitic tufas illustrated in Figure 7a. Base of photo is ~ 0.5 mm wide.

12.3. Evaporites

Most minerals that precipitate from aqueous solutions incorporate fluid inclusions during growth. In biological settings, fluid inclusions capture not only samples of the surrounding water but also biomolecules and microorganisms that are attached to crystal surfaces. Physiological studies of the organisms entrapped in salt suggest that they can maintain viability for several years after incorporation [Norton and Grant, 1988]. Rothschild *et al.* [1994] showed that microbes entrapped in evaporites metabolize both carbon and nitrogen, although at a slower rate. Other authors have suggested that halophilic microorganisms can remain viable in bedded salt for hundreds of millions of years [Norton *et al.*, 1993] (also see review by Javor [1989]). Although the long-term viability of microorganisms within salt is still questioned, salt crystals and brine inclusions appear to provide excellent environments for the long-term preservation of biomolecules. Many ancient salt deposits have been shown to contain a variety of microbial fossils [Tasch, 1963; Bell, 1989; Roucy, 1988; Huval and Vreeland, 1991] and associated biomarkers [Fredrickson *et al.*, 1997].

Salt has been identified as a potentially important exploration target for past or present Martian life [Rothschild, 1990]. In addition to biological information, ancient evaporites may also yield valuable clues about past climate, as well as information about the composition of ancient fluids entrapped as inclusions in salt [Roedder, 1984; Knauth, 1993].

In the presence of an active hydrological cycle, evaporites are quickly dissolved. Consequently, primary evaporites are rare in older rock sequences on Earth. The Precambrian evaporite record mostly consists of crystal pseudomorphs formed when primary evaporite minerals were dissolved and replaced by secondary minerals, such as silica or barite [e.g., Buick and Dunlop, 1990]. However, the situation could be quite different for Mars. Given that the surface hydrological cycle ceased very early on Mars, the crustal residence time for Martian evaporites is likely to be much longer than on Earth, making evaporites an important target.

In playa lake settings, evaporite deposits often form a predictable "bull's eye" pattern with carbonates occurring in marginal basin areas and sulfates and halides being deposited at progressively more basinward locations [Warren, 1989; Eugster and Hardie, 1978]. Because evaporite minerals possess characteristic spectral signatures in the infrared [Kahle, 1986; Gaffey, 1987; Crowley, 1991, 1993; Lane and Christensen, 1997], it may be possible to identify them from Mars orbit using high-resolution remote-sensing methods. The floors of some impact craters on Mars, such as "White Rock" [Forsythe, 1990; Williams and Zimbleman, 1994] and Bequeral Crater (see Oxia Palus NE, Site 148, in Greeley and Thomas [1994]), contain floor deposits that could be evaporites, inclusive of carbonates.

13. Duracrasts and Hardpan Soils

When surface water percolates downward through soils, it leaches out soluble minerals and redeposits them at depth to form surface duricrusts or subsoil hardpans. Hardpan types include calcretes (composed of mostly carbonates), ferricretes (dominated by Fe and Al oxides), and silcrettes (silica-rich soils). Clay-rich hardpans may also form by illuviation (the accumulation of clay-sized particles during the downward percolation of water). Some hardpans (e.g., laminar calcretes) may be biomediated [Verrecchia *et al.*, 1991].

Terrestrial soils typically contain numerous microorganisms

and associated organic materials [Paul and Clark, 1989]. Microbial fossils and biogenic fabrics have been reported from a variety of hardpan soils. In most cases, preservation occurred by the encrustation of organic surfaces, followed by organic matter degradation to form biomolds [Kahle, 1977; Jones and Kahle, 1985]. In some instances, calcrete microfabrics and microbial fossils were preserved by early silica replacement [Vaniman *et al.*, 1994].

The oldest record of land-based microbial life is found in 1.2 billion year old cherts that filled cavities and replaced carbonates along ancient paleokarst surfaces [Horodyski and Knauth, 1994]. Fossil microbiotas associated with these cherts were preserved by the encrustation of exterior cell surfaces by Fe oxides, followed by silica permineralization and replacement.

Mineralized horizons within ancient paleosols could be one of the most widespread exopaleontological targets on Mars. Interestingly, both the Viking lander and Pathfinder missions discovered indurated soils (patchy duricrusts) that are resistant to wind ablation [Moore *et al.*, 1987; Golombek *et al.*, 1997b]. Elemental analyses from both Viking [Toulmin *et al.*, 1977] and Pathfinder [Rieder *et al.*, 1997] suggested enrichments in sulfur and chlorine. This is consistent with the presence of aqueous precipitates like sulfates, halides, or other salts [Clark, 1993].

14. Ground Ice

Sagan [1971] suggested that microorganisms from an earlier, clement period in Martian history might still exist there today in a perpetually frozen state. While the long-term viability of microorganisms in ice over geologically significant time spans is debatable [see Kennedy *et al.*, 1994], entombment in ice has been shown to protect organic materials from degradation for prolonged periods [Gilichinsky, 1995; Gilichinsky *et al.*, 1993]. Freeze drying is a common mode of microbial fossilization in high-latitude desert environments of the Antarctic [see Dom *et al.*, 1998].

From the standpoint of exopaleontology, the major disadvantage of ice is its short crustal residence time. Geomorphic evidence suggests that near-surface ground ice is presently widespread on Mars at latitudes exceeding 40° [Squyres and Carr, 1986]. However, global climate is likely to have changed significantly over the geological history of Mars. Climate forcing may have been mediated by Milankovitch-like cycles similar to those that affect the Earth's climate [Toon *et al.*, 1980; Cutts *et al.*, 1981; Cutts and Lewis, 1982]. Cyclic climatic changes may have produced past episodes of global warming and widespread cryospheric melting. Even more profound and unpredictable climate changes may have occurred owing to chaotic obliquity variations which may have been as high as 60° [Wisdom, 1987]. Such observations suggest that all near-surface ice deposits on Mars are geologically very young. For this reason, Martian ground ice is best regarded as a short-term repository for fossil information.

Although it is appropriate to regard surface ground ice as being restricted temporally, under particular circumstances, ice could provide important opportunities to explore for the remains of extant subsurface organisms. This could be possible for situations in which groundwater has moved into near-surface environments and frozen. Potential mechanisms for the upward movement of deep groundwater include subsurface hydrothermal systems associated with shallow magmatic intrusions and small volcanoes [see Farmer, 1996].

Models of the Martian cryosphere suggest a possibility for

basal melting under the northern polar ice cap of Mars [Clifford, 1987]. Where basal melting existed, there is the possibility for developing localized habitable zones within the shallow cryosphere. Cycles of seasonal melting or outflows of water accompanying subglacial volcanic activity could provide important opportunities for delivering subsurface liquid water to the Martian surface. Under such circumstances, any associated microbiota could be brought into near-surface ground-ice environments and cryopreserved along the margins of polar glaciers. Such situations could provide important opportunities to sample for a Mars "cryopaleontology."

15. Exploring for Prebiotic Chemistry

The record of prebiotic chemical evolution which preceded the origin of life on Earth has been lost through tectonic recycling, weathering, and erosion of the crust. Given its extensive crustal record, Mars probably provides the best opportunity in the solar system for studying prebiotic chemical evolution in a context similar to the primitive Earth. In particular, with an extensively preserved stratigraphy for early Mars, there may be an unprecedented opportunity to explore for a record of important steps in prebiotic chemical evolution. The same basic aqueous sedimentary processes and deposits identified previously as primary targets for a Martian fossil record are also the best candidates preserving a record of prebiotic chemistry.

16. Challenges of Site Selection

High-resolution mapping techniques are essential for precisely locating ancient aqueous sedimentary deposits on Mars and for selecting the best landing sites to explore for evidence of past Martian life [NASA, 1995]. Mantling of the surface by impact ejecta and aeolian deposits may obscure surface outcrops over large areas of the planet's surface. Thus remote-sensing targets could be quite small and localized, even within large sedimentary basins. Given such constraints, spatial resolutions of <100 m/pixel may be required to precisely identify the location of outcrops.

The Thermal Emission Spectrometer (TES) presently in orbit at Mars will produce the first maps of Martian surface composition at a spatial resolution of ~3 km/pixel [Christensen *et al.*, 1992]. During the premapping phase of the current mission, TES provided data for initial mineralogical mapping in the Sinus Meridiani region which revealed large deposits of coarse-grained ("specular") hematite that suggest the activity of near-surface water [Lane *et al.*, 1999]. It is possible that the most important mineral targets for Mars exopaleontology may be in low abundance and widely disseminated through host rocks as cements or veins. At a spatial resolution of 3 km/pixel each data point consists of composite spectrum representing a complex mixture of materials. At low abundances it may be impossible to isolate the signatures of important target minerals without going to higher spatial resolution. This may require follow-up missions to carry out targeted high spatial resolution searches at high-priority sites. Such high spatial resolution orbital spectroscopy is currently planned for the 2001 mission.

During the Mars Surveyor Program, robotic rover mobility is expected to be only a few kilometers during nominal missions [Stoker, 1998]. The landing error ellipse for the Mars Pathfinder Mission was ~150 km long [Golombek *et al.*, 1997a, b]. Because rovers are unlikely to travel beyond a single TES pixel during missions, targeting errors need to be substantially re-

duced to place rovers within reach of high-priority sites identified from orbit. This underscores the importance of a sustained orbital effort to obtain high spatial resolution mineralogical mapping for selected sites to support site selection and to plan surface missions leading up to the sample return currently planned for 2005.

17. Application of the Strategy: Site Priorities for the Pathfinder Mission

The Mars Pathfinder Mission was a Discovery-class mission that delivered a small lander and rover to the surface of Mars using a novel air-bag landing system [Golombek, 1997]. The nominal landing site was selected by the Pathfinder Team on the basis of inputs received from the planetary science community during a landing site workshop [Golombek, 1994]. Constraints for the landing site were 0°–30° North latitude and below the 0.0 global elevation datum. The final landing site (mouth of Ares Vallis outflow channel, southern Chryse Planitia) was selected from more than 20 proposals on the basis of engineering safety concerns as well as the potential for sampling a large number of lithologies within a short distance (few tens of meters) of the lander [Greeley and Kuzmin, 1994]. Independently, this site was also targeted for exopaleontology on the basis of its location at the mouth of a large outflow channel that originated within a chaotic terrain of possible hydrothermal origin [Farmer and Des Marais, 1994c].

17.1. Geological Setting of the Pathfinder Site

The Ares Vallis outflow channel originates within a series of highly fractured, irregular to circular collapsed zones (chaotic terrains [Baker and Milton, 1974]; Figure 3b). These regions consist of broken and jumbled blocks believed to have been formed by the withdrawal of subsurface water [Mars Channel Working Group, 1983; Baker *et al.*, 1992; Nelson and Greeley, 1999]. On a regional scale, the channels are broadly anastomosing networks that include a variety of macroscale and mesoscale flow features [Baker, 1982]. Catastrophic outflowing of water was invoked by Baker and Milton [1974] to explain many outflow channel features on Mars, although the source of the water and the mechanism of its release are more controversial [see Carr, 1996]. Masursky *et al.* [1986] suggested a thermokarst origin for the chaos source regions of many outflow channels, with outflows of water originating from melting of the shallow cryosphere, perhaps as a result of subsurface heating (shallow intrusives). Epithermal and subaerial hydrothermal systems associated with shallow intrusives could have developed at the surface and persisted for prolonged periods [see Gulick, 1998] prior to and following each major outflow event.

Some small-channel systems on the edges of chaotic terrains possess amphitheater-shaped head reaches with a patchy albedo [Farmer *et al.*, 1995a; Farmer, 1996]. Accepting the possibility of a hydrothermal origin for the chaos regions, these sites are logical places for the formation of ancient subaerial thermal spring sinters. In this case, a putative subsurface biota could have been carried up by hydrothermal circulation, colonizing surface springs. The high rates of mineralization typically observed in hydrothermal settings could have provided the needed mechanism for entrapping the microorganisms and/or their by-products. Surface hydrothermal systems on Mars are likely to have been comparatively cool by terrestrial standards [Farmer, 1996]. On Earth, lower-temperature environments appear to be more favorable for the preservation of

organic matter. In the case of Pathfinder, hydrothermal deposits may have been entrained during periodic outflooding events, carried downstream, and deposited at the mouth of Ares Vallis.

17.2. Composition of Rocks and Soils at the Pathfinder Site

Although the Pathfinder Mission was not designed to explore for past life, the alpha proton X-ray spectrometer (APXS) provided our first opportunity to obtain elemental analyses from rocks, an important exopaleontological goal. Although calibrations are still being refined, published APXS data for the rocks analyzed at the Pathfinder site showed enrichments in silica within the range of ~50.0–65.0% by weight [Rieder *et al.*, 1997]. This yields an average igneous composition equivalent to andesite. Similar silica enrichments were also observed for soils. Although some rocks appear to be vesicular, the textures of other rocks are difficult to interpret and could as easily be igneous, sedimentary, or metamorphic in origin. This leaves the possibilities open for a variety of differentiation processes to account for the observed silica enrichment, including the fractional crystallization of a mafic magma, impact shock melting, hydrothermal mineralization, and low-temperature weathering processes.

Clearly, the analysis of rocks using rover instrumentation marks an important first step in the exopaleontological exploration of Mars. However, in the absence of mineralogical and microtextural data it is difficult to evaluate the full significance of APXS data. It is worth noting, however, that silica is a common low-temperature hydrothermal and diagenetic mineral that occurs widely as sedimentary cements, as a fracture-filling mineral, and as vesicle fills (amygdules) in volcanic rocks. At present, none of these possibilities can be ruled out. In 2001, NASA will deliver the flight spare of the Pathfinder rover to the surface of Mars. On the basis of the above discussion, it is recommended that the rover for that mission include a close-up (microscopic) imaging capability to provide important information about rock microtextures. Such textural information could help constrain mineralogical interpretations of elemental data. Beginning with the 2003 mission, rovers are expected to carry a more sophisticated suite of instruments that will obtain a series of in situ microtextural, mineralogical, and organic analyses of rocks as a basis for identifying lithologies and selecting samples for return to Earth. These missions will provide important opportunities for implementing the proposed strategy for exopaleontology.

18. Summary Discussion

In defining a site-selection strategy to explore for a Martian fossil record, a key concept is early diagenetic mineralization. This process entombs microorganisms, stabilizes morphological information, and protects biosignatures during subsequent diagenetic changes. On Earth, geological environments where microorganisms are often preserved in this way include (1) mineralizing spring systems (subaerial, subaqueous, and shallow subsurface hydrothermal systems and cold springs of alkaline lakes), (2) saline/alkaline environments of arid marine shorelines (sabkhas) or terminal (evaporative) lake basins, (3) duricrusts and subsoil hardpan environments formed by the selective leaching and reprecipitation of minerals within soil profiles, and (4) periglacial environments, ground ice, or permafrost (frozen soils) which have captured and cryopreserved microorganisms and associated organic materials.

Deposits formed in these environments have differing crustal residence times, which determines their relative importance as potential targets for a fossil record, whether on the Earth or Mars. For long-term preservation the most favorable host rocks are those made up of densely structured, stable minerals like silica and phosphate. These lithologies, along with fine-grained clay-rich detrital sediments and carbonates, harbor most of the fossil record of early biosphere evolution on Earth. Even if life never developed on Mars, the same types of sedimentary environments and processes identified as being important for preserving a terrestrial fossil record are also key for recording a history of the early evolutionary steps in prebiotic chemistry that preceded the development of life on Earth.

The surface hydrological system of Mars was apparently still active during late heavy bombardment, and impact-related metamorphism and brecciation of the surface materials may have partially overprinted some of the earliest record of aqueous environments. The heavily cratered highlands are likely to consist of a complex mosaic of impact ejecta, including mafic igneous rocks, impact metamorphosed aqueous sedimentary rocks, and discrete sedimentary deposits that have been little altered. Impact-related hydrothermal systems could have been widespread during this time and are likely to have contributed significantly to the inventory of early aqueous sedimentary deposits, both at the surface and in shallow subsurface environments.

Successful implementation of a strategy for Mars exopaleontology will depend on targeting the most favorable landing sites for in situ robotic exploration and sample return. Mineralogy provides the most direct means for interpreting ancient environments and comprises a fundamental step in selecting the sites that have the best chance for having capturing and preserved a record of ancient life or prebiotic chemistry. Given the complexity of these heavily cratered terrains, the identification of exopaleontological targets is likely to require orbital mapping at a spatial resolution that can resolve small outcrops. The aqueous mineral deposits of most interest (silica, phosphate, clays, carbonates, evaporites, oxides, and sulfides) have characteristic spectral signatures and may be identifiable from orbit using hyperspectral methods that allow the identification of discrete mineral signatures within complex mixtures.

During landed missions the collection of samples for return to Earth will require the use of mobile platforms (rovers) capable of reaching well-defined lithological targets. Rovers will need to be instrumented to (1) target rocks from a distance on the basis of mineralogical composition and (2) subsample rocks of appropriate composition [Farmer, 1999].

Finally, the ongoing controversy over signs of life in Martian meteorite ALH84001 suggests that the unambiguous identification of fossil life may require multiple sample returns from one or more aqueous sedimentary environments of the type identified above. Once samples have been returned to Earth, analysis will require highly integrated microanalytical techniques to evaluate biogenicity. In anticipation of Mars sample returns, we need to perfect the use of high-sensitivity, high spatial resolution methods of sample analysis in the analysis of appropriate geological or extraterrestrial materials. This goal can be attained through ongoing studies of ancient terrestrial materials that can serve to advance our understanding of early evolution on Earth while helping to refine our present strategy for Mars exopaleontology.

Acknowledgments. The authors wish to acknowledge constructive critical reviews by John Hayes (Woods Hole Oceanographic Institution) and an anonymous reviewer. We are grateful to Maria Farmer for her assistance in preparing Figure 1, to Hans Hofmann, who generously provided access to thin sections from Belcher Island, Canada, used for Figure 2, and to Mykell Discipulo, who assisted editing of the references. This project was supported by a grant (to J.D.F.) by NASA's Exobiology Program.

References

- Allison, P. A., Konservat-lagerstätten: Cause and classification, *Paleobiology*, 14, 331–344, 1988a.
- Allison, P. A., The role of anoxia in the decay and mineralization of proteinaceous macrofossils, *Paleobiology*, 14, 139–154, 1988b.
- Allison, P. A., and D. E. G. Briggs, Taphonomy of non-mineralized tissues, in *Taphonomy: Releasing the Data of the Fossil Record*, edited by P. A. Allison and D. E. G. Briggs, pp. 25–70, Plenum, New York, 1991a.
- Allison, P. A., and D. E. G. Briggs, Taphonomy of soft-bodied animals, in *The Processes of Fossilization*, edited by S. K. Donovan, pp. 120–140, Columbia Univ. Press, New York, 1991b.
- Allison, P. A., and K. Pye, Early diagenetic mineralization and fossil preservation in modern carbonate concretions, *Palaio*, 9, 561–575, 1994.
- Amy, P. S., and D. L. Haldeman (Eds.), *The Microbiology of the Terrestrial Deep Subsurface*, A. F. Lewis, New York, 1997.
- Baker, V. C., *The Channels of Mars*, Univ. of Tex. Press, Austin, 1982.
- Baker, V. C., and D. J. Milton, Erosion by catastrophic floods on Mars and Earth, *Icarus*, 23, 27–41, 1974.
- Baker, V. R., M. H. Carr, V. C. Gulick, C. M. Williams, and M. S. Marley, Channels and valley networks, in *Mars*, edited by H. H. Kieffer et al., pp. 493–522, Univ. Ariz. Press, Tucson, 1992.
- Baker, V. R., G. Benito, and A. N. Rudoy, Paleohydrology of late Pleistocene superflooding, Altay Mountains, Siberia, *Science*, 259, 348–350, 1993.
- Barlow, N. G., Identification of possible source craters for Martian meteorite ALH 84001, *Proc. SPIE Int. Soc. Opt. Eng.*, 3111, 26–35, 1997.
- Bell, C. M., Saline lake carbonates within an Upper Jurassic-Lower Cretaceous continental red bed sequence in the Atacama region of northern Chile, *Sedimentology*, 36, 651–664, 1989.
- Benson, L., Carbonate deposition, Pyramid Lake Subbasin, Nevada, I, Sequence of formation and elevational distribution of carbonate deposits (tufas), *Palaogeogr. Palaeoclimatol. Palaeoecol.*, 109, 55–87, 1994.
- Berner, R. A., Calcium carbonate concretions formed by the decomposition of organic matter, *Science*, 159, 195–197, 1968.
- Bock, G. R., and J. A. Goode (Ed.), *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, 334 pp., John Wiley, New York, 1996.
- Boston, P. J., M. V. Ivanov, and C. P. McKay, On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars, *Icarus*, 95, 300–308, 1992.
- Brakenridge, G. R., H. E. Newsom, and V. R. Baker, Ancient hot springs on Mars: Origins and paleoenvironmental significance of small Martian valleys, *Geology*, 13, 859–862, 1985.
- Brocks, J. J., G. A. Logan, R. Buick, and R. E. Summons, Archean molecular fossils on the early rise of eukaryotes, *Science*, 285, 1033–1036, 1999.
- Buick, R., and J. S. R. Dunlop, Evaporitic sediments of Early Archean age from the Warrawoona Group, North Pole, Western Australia, *Sedimentology*, 37, 247–277, 1990.
- Cady, S. L., and J. D. Farmer, Fossilization processes in siliceous thermal springs: Trends in preservation along thermal gradients, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 150–173, John Wiley, New York, 1996.
- Carr, M. H., *The Surface of Mars*, 232 pp., Yale Univ. Press, New Haven, Conn., 1981.
- Carr, M. H., Water on Mars, *Nature*, 326, 30–35, 1987.
- Carr, M. H., *Water on Mars*, Oxford Univ. Press, New York, 1996.
- Chang, S., The planetary setting of prebiotic evolution, in *Early Life on Earth: Nobel Symposium No. 84*, edited by S. Bengtson, pp. 10–23, Columbia Univ. Press, New York, 1994.
- Chang, S., Prebiotic chemistry on Mars, *Eos Trans. AGU*, 76(46), 334, 1995.
- Chapman, M. G., Evidence, age, and thickness of a frozen paleolake in Utopia Planitia, Mars, *Icarus*, 109, 393–406, 1994.
- Christensen, P. R., et al., Thermal emission spectrometer experiment: Mars Observer Mission, *J. Geophys. Res.*, 97(E5), 7719–7734, 1992.
- Chyba, C., and C. Sagan, Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: An inventory for the origins of life, *Nature*, 355, 125–131, 1992.
- Clark, B. C., Geochemical components in Martian soil, *Geochim. Cosmochim. Acta*, 57, 4574–4581, 1993.
- Clark, B. C., Surviving the limits of life at the surface of Mars, *J. Geophys. Res.*, 103(E12), 28,545–28,555, 1998.
- Clifford, S. M., Polar basal melting on Mars, *J. Geophys. Res.*, 92(B9), 9135–9152, 1987.
- Clifford, S. M., A model for the hydrologic and climatic behavior of water on Mars, *J. Geophys. Res.*, 98(E6), 10,973–11,016, 1993.
- Compton, J. S., L. B. Williams, and R. E. Ferrell Jr., Mineralization of organogenic ammonium in the Monterey Formation, Santa Maria and San Joaquin basins, California, USA, *Geochim. Cosmochim. Acta*, 56, 1979–1991, 1992.
- Cook, T. L., and D. S. Stakes, Biogeological mineralization in deep-sea hydrothermal deposits, *Science*, 267, 1975–1979, 1995.
- Council, T. C., and P. C. Bennett, Geochemistry of Ikaite Formation at Mono Lake, California: Implications for the origin of tufa mounds, *Geology*, 21, 971–974, 1993.
- Crowley, J. K., Visible and near-infrared (0.4–2.5 μm) reflectance spectra of playa evaporite minerals, *J. Geophys. Res.*, 96(B10), 16,231–16,240, 1991.
- Crowley, J. K., Mapping playa evaporite minerals with AVIRIS data: A first report from Death Valley, California, *Remote Sens. Environ.*, 44, 1–25, 1993.
- Crown, D. A., K. H. Price, and R. Greeley, Geologic evolution of the east rim of the Hellas Basin, Mars, *Icarus*, 100, 1–25, 1992.
- Cutts, J. A., and B. H. Lewis, Models of climate cycles recorded in Martian polar layered deposits, *Icarus*, 50, 216–244, 1982.
- Cutts, J. A., J. B. Pollack, A. D. Howard, and O. B. Toon, Quasi-periodic climatic changes on Mars and Earth, *Eos Trans. AGU*, 62(45), 755–759, 1981.
- Des Marais, D. J., Long-term evolution of the biogeochemical carbon cycle, in *Geomicrobiology: Interactions Between Microbes and Minerals*, edited by J. E. Banfield and K. H. Nealson, pp. 429–448, Mineral. Soc. of Am., Washington, D. C., 1997.
- Dorn, P. T., R. A. Wharton Jr., D. J. Des Marais, and C. P. McKay, Antarctic paleolake sediments and the search for extinct life on Mars, *J. Geophys. Res.*, 103(E12), 28,481–28,493, 1998.
- Dymond, J., R. W. Collier, and M. E. Warwood, Bacterial mats from Crater Lake, Oregon and their relationship to possible deep-lake hydrothermal venting, *Nature*, 342(6250), 673–675, 1989.
- Eugster, H. P., and L. A. Hardie, Saline lakes, in *Lakes: Chemistry, Geology, and Physics*, edited by A. Lerman, pp. 237–293, Springer-Verlag, New York, 1978.
- Farmer, J. D., Mars exopaleontology, *Palaio*, 10(3), 197–198, 1995.
- Farmer, J. D., Hydrothermal processes on Mars: An assessment of present evidence, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 273–299, John Wiley, New York, 1996.
- Farmer, J. D., Thermophiles, early biosphere evolution, and the origin of life on Earth: Implications for the exobiological exploration of Mars, *J. Geophys. Res.*, 103(E12), 28,457–28,461, 1998.
- Farmer, J. D., Implementing a strategy to explore for ancient Martian life, in *The Search for Life on Mars*, edited by J. A. Hiscox, pp. 58–65, Br. Interplanet. Soc., London, 1999.
- Farmer, J. D., and D. J. Des Marais, Exopaleontology and the search for a fossil record on Mars, *Lunar Planet. Sci.*, XXV, 367–368, 1994a.
- Farmer, J. D., and D. J. Des Marais, Biological versus inorganic processes in stromatolite morphogenesis: Observations from mineralizing systems, in *Microbial Mats: Structure, Development and Environmental Significance*, edited by L. J. Stal and P. Caumette, pp. 61–68, Springer-Verlag, New York, 1994b.
- Farmer, J. D., and D. J. Des Marais, Mars Pathfinder site priorities for exobiology, in *Mars Pathfinder Landing Site Workshop*, edited by M. Golombek, *Tech. Rep. 94-04*, pp. 26–27, Lunar and Planet. Inst., Houston, Tex., 1994c.
- Farmer, J. D., D. J. Des Marais, and R. Greeley, Exopaleontology at the Pathfinder landing site, *Lunar Planet. Sci.*, XXVI, 393–394, 1995a.
- Farmer, J. D., D. J. Des Marais, R. Greeley, R. Landheim, and H. Klein, Site selection for Mars Exobiology, *Adv. Space Res.*, 15(3), 157–162, 1995b.

- Farmer, J. D., S. L. Cady, and D. J. Des Marais, Fossilization processes in thermal springs, *Geol. Soc. Amer. Ab. Programs*, 27(6), 305, 1995c.
- Forsythe, R. D., A case for Martian salts and saline lakes during the Noachian, *Lunar Planet. Sci.*, XXI, 379-380, 1990.
- Fredrickson, J. K., and T. C. Onstott, Microbes deep inside the Earth, *Sci. Am.*, 275(4), 42-47, 1996.
- Fredrickson, J. K., T. C. Onstott, T. J. Bailey, and D. P. Chandler, Preservation of Haloarchaea and their macromolecular constituents in brine inclusions from bedded salt deposits, paper presented at Sixth Symposium on Chemical Evolution and the Origin and Evolution of Life, NASA Ames Res. Cent., 1997.
- Gaffey, S. J., Spectral reflectance of carbonate minerals in the visible and near infrared (0.35-2.55 μm): Anhydrous carbonate minerals, *J. Geophys. Res.*, 92(B2), 1429-1440, 1987.
- Garcia-Pichel, F., and R. W. Castenholz, Characterization and biological implications of scytonemin, a cyanobacterial sheath pigment, *J. Phycol.*, 27(3), 395-409, 1991.
- Gilichinsky, D. A., Permafrost microbiology, *Permafrost Periglacial Processes*, 6, 281-291, 1995.
- Gilichinsky, D. A., V. S. Soina, and M. A. Petrova, Cryoprotective properties of water in the Earth cryolithosphere and its role in exobiology, *Orig. Life Evol. Biosphere*, 23, 65-75, 1993.
- Goetz, A. F. H., B. N. Rock, and L. C. Rowan, Remote sensing for exploration: An overview, *Econ. Geol.*, 78, 573-590, 1983.
- Goetz, A. F. H., G. Vane, J. E. Solomon, and B. N. Rock, Imaging spectrometry for Earth remote sensing, *Science*, 228, 1147-1153, 1985.
- Gold, T., The deep, hot biosphere, *Proc. Natl. Acad. Sci. U. S. A.*, 89, 6045-6049, 1992.
- Goldspiel, J. M., and S. W. Squyres, Ancient aqueous sedimentation on Mars, *Icarus*, 89, 392-410, 1991.
- Golombek, M., Mars Pathfinder Landing Site Workshop, pp. 49, *Tech. Rep. 94-04*, 49 pp., Lunar and Planet. Inst., Houston, Tex., 1994.
- Golombek, M. P., The Mars Pathfinder Mission, *J. Geophys. Res.*, 102(E2), 3953-3965, 1997.
- Golombek, M. P., R. A. Cook, H. J. Moore, and T. J. Parker, Selection of the Mars Pathfinder landing site, *J. Geophys. Res.*, 102(E2), 3967-3988, 1997a.
- Golombek, M. P., et al., Overview of the Mars Pathfinder Mission and assessment of landing site predictions, *Science*, 278(5344), 1743-1748, 1997b.
- Golubic, S., I. Friedmann, and J. Schneider, The lithobiontic ecological niche, with special reference to microorganisms, *J. Sediment. Petrol.*, 51, 475-478, 1981.
- Greeley, R., and R. Kuzmin, Strategy for selecting Mars Pathfinder landing sites, in *Mars Pathfinder Landing Site Workshop*, edited by M. Golombek, pp. 29-30, *Tech. Rep. 94-04*, Lunar Planet. Inst., Houston, Tex., 1994.
- Greeley, R., and P. Thomas (Eds.), *Mars Landing Site Catalog*, NASA Ref. Publ. 1238, vol. 2, 1994.
- Griffeth, L. L., and E. L. Shock, A geochemical model for the formation of hydrothermal carbonates on Mars, *Nature*, 377, 406-408, 1995.
- Grin, E. A., and N. A. Cabrol, Limnologic analysis of Gusev Crater paleolake, Mars, *Icarus*, 130, 461-474, 1997.
- Grotzinger, J. P., Trends in Precambrian carbonate sediments and their implication for understanding evolution, in *Early Life on Earth: Nobel Symposium No. 84*, edited by S. Bengtson, pp. 245-258, Columbia Univ. Press, New York, 1994.
- Gulick, V., Magmatic intrusions and hydrothermal systems: Implications for the formation of Martian fluvial valleys and life, *J. Geophys. Res.*, 103(E8), 19,365-19,387, 1998.
- Henley, R. W., Chemical and physical context for life in terrestrial hydrothermal systems: Chemical reactors for the early development of life and hydrothermal ecosystems, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 61-82, John Wiley, New York, 1996.
- Heinrichs, S. M., and W. S. Reeburgh, Anaerobic mineralization of marine sediment organic matter: Rates and role of anaerobic processes in the oceanic carbon economy, *Geomicrobiol. J.*, 5, 191-237, 1987.
- Hofmann, B. A., and J. D. Farmer, Microbial fossils from terrestrial subsurface hydrothermal environments: Examples and implications for Mars, in *Conference on Early Mars: Geologic and Hydrologic Evolution, Physical and Chemical Environments, and the Implications for Life*, edited by S. M. Clifford et al., pp. 40-41, *Contrib. 916*, Lunar and Planet. Inst., Houston, Tex., 1997.
- Hofmann, H. J., Precambrian fossils, pseudofossils and problematica in Canada, *Bull. Geol. Surv. Can.*, 189, 1-146, 1971.
- Hofmann, H. J., Precambrian microflora, Belcher Islands, Canada: Significance and systematics, *J. Paleontol.*, 50(6), 1040-1073, 1976.
- Holland, H. D., *The Chemical Evolution of the Atmosphere and Oceans*, 582 pp., Princeton Univ. Press, Princeton, N. J., 1984.
- Horn, R. A., Exploration strategies for hydrothermal deposits, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 236-245, John Wiley, New York, 1996.
- Horodyski, R. J., and L. P. Knauth, Life on land in the Precambrian, *Science*, 263, 494-498, 1994.
- Horowitz, N. H., Biological water requirements, in *Strategies of Microbial Life in Extreme Environments*, edited by M. Shilo, pp. 15-27, Verlag Chemie, New York, 1979.
- Huntington, J. F., The role of remote sensing in finding hydrothermal deposits, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 214-230, John Wiley, New York, 1996.
- Huval, J. H., and R. H. Vreeland, Taxonomy of halophilic bacteria from underground saline waters and salt formations, in *General and Applied Aspects of Halophilic Bacteria*, edited by F. Rodriguez-Valera, pp. 53-60, Plenum, New York, 1991.
- Jakosky, B. M., Mars volatile evolution: Evidence from stable isotopes, *Icarus*, 94, 14-31, 1991.
- Javor, B., *Hypersaline Environments*, 334 pp., Springer-Verlag, New York, 1989.
- Jones, B., and C. F. Kahle, Dendritic calcite crystals formed by calcification of algal filaments in a vadose environment, *J. Sediment. Petrol.*, 56(2), 217-227, 1985.
- Jones, B., and R. W. Renaut, Formation of silica oncoids around geysers and hot springs at El Tatio, northern Chile, *Sedimentology*, 44, 287-384, 1997.
- Jones, B., R. W. Renaut, and M. R. Rosen, Biogenicity of silica precipitation around geysers and hot-spring vents, North Island, New Zealand, *J. Sediment. Res.*, 67, 88-104, 1997.
- Kahle, A. B., Surface emittance, temperature, and thermal inertia derived from thermal infrared multispectral scanner (TIMS) data for Death Valley, California, *Geophysics*, 52, 858-874, 1986.
- Kahle, C. F., Origin of subaerial Holocene calcareous crusts: Role of algae, fungi and sparmicritization, *Sedimentology*, 24, 413-435, 1977.
- Kennedy, M. J., S. L. Reader, and L. M. Swierczynski, Preservation records of micro-organisms: Evidence of the tenacity of life, *Microbiology*, 140, 2513-2529, 1994.
- Klein, H. P., The Viking biology experiments: Epilogue and prologue, *Orig. Life Evol. Biosphere*, 21, 255-261, 1992.
- Klein, H. P., The search for life on Mars: What we learned from Viking, *J. Geophys. Res.*, 103(E12), 28,463-28,466, 1998.
- Klein, H. P., and J. D. Farmer, Status of the search for life on Mars, in *Progress in the Search for Extraterrestrial Life*, edited by G. S. Shostek, *Astron. Soc. Pac. Conf. Ser.*, 74, 65-71, 1995.
- Knauth, P., Ancient sea water, *Nature*, 362, 290-291, 1993.
- Knoll, A. H., Exceptional preservation of photosynthetic organisms in silicified carbonates and silicified peats, *Philos. Trans. R. Soc. London, Ser. B*, 311, 111-122, 1984.
- Komar, P. D., Comparisons of the hydraulics of water flows in Martian outflow channels with flows of similar scale on Earth, *Icarus*, 37, 156-181, 1979.
- Komar, P. D., Modes of sediment transport in channelized water flows with ramifications to the erosion of the Martian outflow channels, *Icarus*, 43, 317-329, 1980.
- Kretzschmar, M., Fossile Pilze in Eisen-Stromatolithen von Warstein (Rheinisches Schiefergebirge), *Facies*, 7, 237-260, 1982.
- Kruse, F. A., K. S. Kierein-Young, and J. W. Boardman, Mineral mapping at Cuprite, Nevada with a 63-channel imaging spectrometer, *Photogramm. Eng. Remote Sens.*, 56, 83-92, 1990.
- Kuhn, W. R., and S. K. Atreya, Solar radiation incident on the Martian surface, *J. Mol. Evol.*, 14, 57-64, 1979.
- Landheim, R., N. Cabrol, R. Greeley, and J. Farmer, Stratigraphic assessment of Gusev crater as an exobiology landing site, *Lunar Planet. Sci.*, XXV, 769-770, 1994.
- Lane, M. D., and P. R. Christensen, Thermal infrared emission spectroscopy of anhydrous carbonates, *J. Geophys. Res.*, 102(E11), 25,581-25,592, 1997.
- Lane, M. D., R. V. Morris, and P. R. Christensen, An extensive deposit

- of crystalline hematite in Terra Meridiani, Mars, *Lunar Planet. Sci. [CD-ROM]*, XXX, abstract 1461, 1999.
- Lockley, M. G., and A. Rice, Volcanism and fossil biotas, *Spec. Pap. Geol. Soc. Am.*, 244, 125 pp., 1990.
- Lucas, J., and L. E. Prevot, Phosphates and fossil preservation, in *Taphonomy: Releasing the Data of the Fossil Record*, edited by P. A. Allison and D. E. G. Briggs, pp. 389–409, Plenum, New York, 1991.
- Luchitta, B. K., Ice and debris in the fretted terrain, Mars, *Proc. Lunar Planet. Sci. Conf. 14th, J. Geophys. Res.*, 89, suppl., B409–B418, 1984.
- Madigan, M. T., J. M. Martinko, and J. Parker, *Brock Biology of Microorganisms*, 8th ed., Prentice-Hall, Englewood Cliffs, N. J., 1996.
- Mars Channel Working Group, Channels and valleys on Mars, *Geol. Soc. Am. Bull.*, 94, 1035–1054, 1983.
- Masursky, H., An overview of geologic results from Mariner 9, *J. Geophys. Res.*, 78(20), 4009–4030, 1973.
- Masursky, H., M. G. Chapman, A. L. J. Dial, and M. E. Strobell, Episodic channeling punctuated by volcanic flows in Mangala Valles region, Mars, *NASA Tech. Manual*, 88383, 459–461, 1986.
- McKay, C. P., and W. L. Davis, Duration of liquid water habitats on Mars, *Icarus*, 90, 214–221, 1991.
- McKay, C. P., and C. R. Stoker, The early environment and its evolution on Mars: Implications for life, *Rev. Geophys.*, 27, 189–214, 1989.
- McKay, D. S., E. K. Gibson, K. L. Thomas-Keptra, H. Vali, C. S. Romanek, S. J. Clemett, X. D. F. Chiller, C. R. Maechling, and R. N. Zare, Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH 84001, *Science*, 273, 924–930, 1996.
- McSween, H. Y., Jr., What have we learned about Mars SNC meteorites?, *Meteoritics*, 29, 757–779, 1994.
- Mendelson, C. V., J. Bauld, R. J. Horodyski, J. H. Lipps, T. B. Moore, and J. W. Schopf, Proterozoic and selected Cambrian microfossils: Prokaryotes and protists, in *The Proterozoic Biosphere: A Multidisciplinary Study*, edited by J. W. Schopf and C. Klein, pp. 175–244, Cambridge Univ. Press, New York, 1992.
- Mojzsis, S. J., and G. Arrhenius, Phosphates and carbon on Mars: Exobiological implications and sample return considerations, *J. Geophys. Res.*, 103(E12), 28,495–28,511, 1998.
- Mojzsis, S. J., G. Arrhenius, K. D. McKeegan, T. M. Harrison, A. P. Nutman, and C. R. L. Friend, Evidence for life on Earth before 3,800 million years ago, *Nature*, 384, 55–59, 1996.
- Moll, D. M., and J. R. Vestal, Survival of microorganisms in smectite clays: Implication for Martian exobiology, *Icarus*, 98, 233–239, 1992.
- Moore, H. J., R. E. Hutton, G. D. Clow, and C. R. Spitzer, Physical properties of the surface materials of the Viking landing sites on Mars, *U.S. Geol. Surv. Prof. Pap.*, 1389, 222 pp., 1987.
- NASA, An exobiological strategy for Mars exploration, *NASA Spec. Publ.*, 530, 56 pp., 1995.
- Nealson, K. H., The limits of life on Earth and searching for life on Mars, *J. Geophys. Res.*, 102(E10), 23,675–23,686, 1997.
- Nelson, D. M., and R. Greeley, Geology of the Xanthe Terra outflow channels and the Mars Pathfinder landing site, *J. Geophys. Res.*, 104(E4), 8653–8669, 1999.
- Newsom, H. E., Hydrothermal alteration of impact melt sheets with implications for Mars, *Icarus*, 44, 204–216, 1980.
- Norton, C. F., and W. D. Grant, Survival of halobacteria within fluid inclusions in salt crystals, *J. Gen. Microbiol.*, 134, 1365–1373, 1988.
- Norton, C. F., T. J. McGenity, and W. D. Grant, Archaeal halophiles (halobacteria) from two British salt mines, *J. Gen. Microbiol.*, 139, 1077–1081, 1993.
- Nutman, A. P., S. Mojzsis, and C. R. L. Frind, Recognition of >3850 Ma water-lain sediments in West Greenland and their significance for the early Archaean Earth, *Geochim. Cosmochim. Acta*, 61(12), 2475–2484, 1997.
- Oberbeck, V. R., and G. Fogleman, Estimates of the maximum time required to originate life, *Orig. Life Evol. Biosphere*, 19, 549–560, 1989.
- Paul, E. A., and F. E. Clark, *Soil Microbiology and Biogeochemistry*, 275 pp., Academic, San Diego, Calif., 1989.
- Pedersen, K., The deep subterranean biosphere, *Earth Sci. Rev.*, 34, 243–260, 1993.
- Pieri, D. C., Martian valleys: Morphology, distribution, age and origin, *Science*, 210, 895–897, 1980.
- Rieder, R., T. Economou, H. Wanke, A. Turkevich, J. Crisp, J. Bruckner, G. Dreibus, and H. Y. McSween Jr., The chemical composition of Martian soil and rocks returned by the mobile Alpha Proton X-Ray Spectrometer: Preliminary results from the X-Ray Mode, *Science*, 278, 1771–1774, 1997.
- Röedder, E., The fluids in salt, *Am. Mineral.*, 69, 413–439, 1984.
- Rolfe, W. D. I., G. P. Durant, A. E. Fallick, A. J. Hall, D. J. Large, A. C. Scott, T. R. Smithson, and G. M. Walkden, An early terrestrial biota preserved by Visean vulcanicity in Scotland, *Spec. Pap. Geol. Soc. Am.*, 244, 13–24, 1990.
- Rothschild, L. J., Earth analogs for Martian life: Microbes in evaporites, A new model system for Mars, *Icarus*, 88, 246–260, 1990.
- Rothschild, L. J., L. J. Giver, M. R. White, and R. L. Mancinelli, Metabolic activity of microorganisms in evaporites, *J. Phycol.*, 30, 431–438, 1994.
- Roucy, J. M., Evaporite-hydrocarbon relationships: The association laminites-reefs-evaporites in the Messinian of the Mediterranean, *Mem. Mus. Natl. Hist. Nat. Ser. C Paris*, 55, 43–70, 1988.
- Sagan, C., The long winter model of Martian biology: A speculation, *Icarus*, 15, 511–514, 1971.
- Schaefer, M. W., Aqueous geochemistry on early Mars, *Geochim. Cosmochim. Acta*, 57, 4619–4625, 1993.
- Schidlowski, M., Early terrestrial life: Problems of the oldest record, in *Chemical Evolution: Self-Organization of the Macromolecules of Life*, edited by J. Chela-Flores et al., pp. 65–79, A. Deepak, Hampton, Va., 1995.
- Schidlowski, M., J. M. Hayes, and I. R. Kaplan, Isotopic inference of ancient biochemistries: Carbon, sulfur, hydrogen, and nitrogen, in *Earth's Earliest Biosphere: Its Origin and Evolution*, edited by J. W. Schopf, pp. 149–186, Princeton Univ. Press, Princeton, N. J., 1983.
- Scholl, D. W., and W. H. Taft, Algae, contributors to the formation calcareous tufa, Mono Lake, California, *J. Sediment. Petrol.*, 34, 309–319, 1964.
- Schopf, J. W., Microfossils of the Early Archaean Apex chert: New evidence of the antiquity of life, *Science*, 260, 640–646, 1993.
- Schopf, J. W., and M. R. Walter, Archaean microfossils: New evidence of ancient microbes, in *The Earth's Earliest Biosphere: Its Origins and Evolution*, edited by J. W. Schopf, pp. 214–239, Princeton Univ. Press, Princeton, N. J., 1983.
- Scott, D. H., and M. G. Chapman, Mars Elysium basin: Geologic/volumetric analyses of a young lake and exobiological implications, *Lunar Planet. Sci.*, XXI, 669–677, 1991.
- Scott, D. H., J. W. Rice Jr., and J. M. Dohm, Martian paleolakes and waterways: Exobiological implications, *Orig. Life Evol. Biosphere*, 21, 189–198, 1991.
- Sharp, R. P., and M. C. Malin, Channels on Mars, *Geol. Soc. Am. Bull.*, 86, 593–609, 1975.
- Shock, E. L., and M. D. Schulte, Organic synthesis during fluid mixing in hydrothermal systems, *J. Geophys. Res.*, 103(E12), 28,513–28,527, 1998.
- Simonson, B. M., and K. E. Carney, Roll-up structures of in situ microbial mats in late Archaean deep shelf environments, *Palaios*, 14, 13–24, 1999.
- Sleep, N. H., and K. Zahnle, Refugia from asteroid impacts on early Mars and the early Earth, *J. Geophys. Res.*, 103(E12), 28,529–28,544, 1998.
- Sleep, N. H., K. J. Zahnle, J. F. Kasting, and H. Morowitz, Annihilation of ecosystems by large asteroid impacts on the early Earth, *Nature*, 342, 139–142, 1989.
- Squyres, S. W., Martian fretted terrain: Flow of erosional debris, *Icarus*, 34, 600–613, 1978.
- Squyres, S. W., Urey Prize Lecture: Water on Mars, *Icarus*, 79, 229–288, 1989.
- Squyres, S. W., and M. H. Carr, Geomorphic evidence for the distribution of ground ice on Mars, *Science*, 231, 249–252, 1986.
- Squyres, S. W., D. E. Wilhelms, and A. C. Moosman, Large-scale volcano-ground ice interactions on Mars, *Icarus*, 70, 385–408, 1987.
- Stetter, K. O., Hyperthermophiles in the history of life, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. A. Goode, pp. 1–18, John Wiley, New York, 1996.
- Stevens, T. O., Subsurface microbiology and the evolution of the biosphere, in *The Microbiology of the Terrestrial Deep Subsurface*, edited by P. S. Amy and D. L. Haldeman, pp. 205–223, A. F. Lewis, New York, 1997.
- Stevens, T. O., and J. P. McKinley, Lithoautotrophic microbial ecosystems in deep basalt aquifers, *Science*, 270, 450–454, 1996.
- Stoker, C., The search for life on Mars: The role of rovers, *J. Geophys. Res.*, 103(E12), 28,557–28,575, 1998.

- Summons, R. E., and M. R. Walter, Molecular fossils and microfossils of prokaryotes and protists from Proterozoic sediments, *Am. J. Sci.*, 290-A, 212-244, 1990.
- Summons, R. E., L. L. Jahnke, and B. R. T. Simoneit, Lipid biomarkers for bacterial ecosystems: Studies of cultured organisms, hydrothermal environments and ancient sediments, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. A. Goode, pp. 174-194, John Wiley, New York, 1996.
- Tasch, P., Fossil content of salt and associated evaporites, in *Symposium on Salt*, edited by A. C. Bersticker, K. E. Hoekstra, and J. F. Hall, pp. 96-102, Northern Ohio Geol. Soc. of Cleveland, 1963.
- Tivey, M. K., Modeling chimney growth and associated fluid flow at seafloor hydrothermal vent sites, in *Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions*, *Geophys. Monogr. Ser.*, vol. 91, edited by S. E. Humphris et al., pp. 158-177, AGU, Washington, D. C., 1995.
- Toon, O. B., J. B. Pollack, W. Ward, J. A. Burns, and K. Bilski, The astronomical theory of climatic 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. Christian, P. H. Evans, and W. C. Kelliher, Geochemical and mineralogical interpretation of the Viking inorganic chemical results, *J. Geophys. Res.*, 82, 4625-4634, 1977.
- Towe, K. M., S. Bengtson, M. A. Fedonkin, H. J. Hofmann, C. Manikiewicz, and B. N. Runnegar, Proterozoic and earliest Cambrian carbonaceous remains, trace and body fossils, in *The Proterozoic Biosphere: A Multidisciplinary Study*, edited by J. W. Schopf and C. Klein, pp. 343-424, Cambridge Univ. Press, New York, 1992.
- Trewin, N. H., The Rhynie cherts: An early Devonian ecosystem preserved by hydrothermal activity, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 131-145, John Wiley, New York, 1996.
- Vaniman, D. T., S. J. Chipera, and D. L. Bish, Pedogenesis of siliceous calcretes at Yucca Mountain, Nevada, *Geoderma*, 63, 1-17, 1994.
- Verrecchia, E. P., J. Ribier, M. Patillion, and K. E. Rolko, Stromatolitic origin for desert laminar calcretes, *Naturwissenschaften*, 78, 505-507, 1991.
- Walter, M. R., Ancient hydrothermal ecosystems on Earth: A new paleobiological frontier, in *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, edited by G. Bock and J. Goode, pp. 112-127, John Wiley, New York, 1996.
- Walter, M. R., Stromatolites: The main source of information on the evolution of the early benthos, in *Early Life on Earth: Nobel Symposium No. 84*, edited by S. Bengtson, pp. 270-286, Columbia Univ. Press, New York, 1994.
- Walter, M. R., and D. J. Des Marais, Preservation of biological information in thermal spring deposits: Developing a strategy for the search for a fossil record on Mars, *Icarus*, 101, 129-143, 1993.
- Walter, M. R., J. Bauld, and T. D. Brock, Siliceous algal and bacterial stromatolites in hot springs and geyser effluents of Yellowstone National Park, *Science*, 178, 402-405, 1972.
- Walter, M. R., D. Rulin, and R. J. Horodyski, Coiled carbonaceous megafossils from the middle Proterozoic of Jixian (Tianjin) and Montana, *Am. J. Sci.*, 290-A, 133-148, 1990.
- Walter, M. R., D. J. Des Marais, J. D. Farmer, and N. W. Hinman, Paleobiology of mid-Paleozoic thermal spring deposits in the Drummond Basin, Queensland, Australia, *Palaos*, 11(6), 497-518, 1996.
- Walter, M. R., S. McLoughlin, A. N. Drinnan, and J. D. Farmer, Palaeontology of Devonian-Carboniferous thermal spring deposits, Drummond Basin, Australia, *Alcheringa*, 22, 285-314, 1998.
- Warren, J. K., *Evaporite Sedimentology: The Importance of Hydrocarbon Accumulation*, 285 pp., Prentice-Hall, Englewood Cliffs, N. J., 1989.
- Williams, S. H., and J. R. Zimbelman, "White Rock": An eroded Martian lacustrine deposit(?), *Geology*, 22, 107-110, 1994.
- Wisdom, J., Urey Prize lecture: Chaotic dynamics in the solar system, *Icarus*, 72, 241-275, 1987.
- Xiao, S., Y. Zhang, and A. H. Knoll, Three-dimensional preservation of algae and animal embryos in a Neoproterozoic phosphorite, *Nature*, 391, 553-558, 1998.
- Zierenberg, R. A., and P. Schiffman, Microbial control of silver mineralization at a sea-floor hydrothermal site on the northern Gorda Ridge, *Nature*, 348, 155-157, 1990.
- D. J. Des Marais, NASA Ames Research Center, MS 239-4, Moffett Field, CA 94035-1000. (desmarais@mail.arc.nasa.gov)
- J. D. Farmer, Department of Geology, Arizona State University, Box 871404, Tempe, AZ 85287-1404. (jfarmer@asu.edu)

(Received March 16, 1998; revised March 10, 1999; accepted March 25, 1999.)