AN OVERVIEW OF THE ORIGIN OF LIFE: THE CASE FOR BIOLOGICAL PROSPECTING ON MARS

JULIAN A. HISCOX
School of Animal and Microbial Sciences, PO Box 228, Reading, RG6 6AJ, UK
E-mail: j.a.hiscox@reading.ac.uk

Abstract. Studies of the Earth's earliest biosphere have suggested a close coupling between the evolution of early life forms and the physical and chemical evolution of the planetary surface. From a biological perspective there were many similarities between early Earth and early Mars. This has led to the idea that an origin of life event may have occurred on Mars, leading to the development of microbial life. Various theories have been advanced to explain the origin of life on Earth, and these are reviewed with relevance to Mars. If traces of past or present biogenic activity are to be found on Mars, then the most likely place to prospect is several kilometers below the surface where liquid water might be stable. Such prospecting may best lend itself to human exploration.

Keywords: Biogenic traces, exobiological prospecting, human exploration, origin of life, Mars, Raman spectroscopy, robotic exploration

1. Introduction

Whilst the way in which life evolves has been elucidated from the species to the molecular level, the origin of life remains one of the most vexing issues in biology and philosophy. Historically the question has been answered differently during different eras and at different stages of civilization. We know it is almost certain that no steps towards the origin of life could have occurred on the Earth's surface until about 4.2 billion years ago, after the Earth's crust formed and the amount of meteorite impacts had subsided so that the environment was no longer in constant upheaval (Oberbeck and Mancinelli, 1994; Schwartzman et al., 1993). On the other hand the fossil record strongly supports the existence of cellular life 3.6 billion years ago (Schopf and Parker, 1987) and indirect evidence exists for biological activity as early as 3.8 to 4 billion years ago (Mojzsis et al., 1996; Schidlowski, 1988). The time window for an origin of life event appears to be about 0.4 billion years. Whilst molecular genetics and the fossil record have helped chart the evolution of modern day life (Schopf, 1989; Woese, 1987), locating geological remains of the origin of life is probably impossible, simply due to the reworking of the Earth's surface through plate tectonics and erosion. How can we begin to investigate the origin of life?

Before asking what happened in this 0.4 billion-year time window, it is prudent to inquire what type of life resulted. The oldest known remains of life appear

Earth, Moon and Planets **87:** 191–212, 2001.

amazingly complex. Presumably a molecule called deoxyribonucleic acid (DNA), as with all modern day organisms (bar some viruses), was used to store the genetic information. DNA is composed of four chemical units, called bases; adenine (A), thymine (T), cytosine (C), and guanine (G). Like a computer program, it is the sequential arrangement of these bases, in groups of three, that carries the genetic information. Also, these microfossils appear to be surrounded by some sort of membrane, therefore everything inside them was enclosed. More importantly, because there are many similar "bacteria" all joined together, this would imply that the bacteria were dividing (replicating) and therefore making daughter bacteria. With this knowledge in hand, the question of the origin of life now splits into five:
(i) How has the Earth remained continuously habitable for the past 4 billion years?
(ii) How did the building blocks of life arise?
(iii) How did they form into molecules that stored genetic information?
(iv) How did this information make copies of itself (called replication)?
(v) How did membranes evolve to encapsulate this information?

2. Establishing the Initial Conditions from Which Life Emerged – Habitable Zone Theory

There is a close coupling between life and geological and atmospheric conditions (McKay, 1991). A planet, such as the Earth, must satisfy a number of conditions in order to support the evolution of life based on terrestrial paradigms. It must have liquid water over a biologically significant period of time and other compounds, including the so-called CHNOPS elements. These are carbon, hydrogen, nitrogen, oxygen, phosphorus and sulphur. Liquid water not only acts as a medium for chemical reactions but is also an integral part of biological systems, both at the structural and molecular level. Therefore habitable planets (and moons), if they are to support surface liquid water, must lie within an orbital zone that is thermally compatible with life – where the average global temperature lies a little below the freezing point of water up to boiling point (Kasting et al., 1993). In the case of the Solar System, the orbital zone compatible with surface liquid water (the habitable zone – HZ) extends from just within the orbit of the Earth to just outside the orbit of Mars.

Earth has remained continuously habitable for at least 3.8 billion years, despite a large increase in stellar luminosity with time. The increase in solar flux was probably offset by a decrease in atmospheric carbon dioxide concentration caused by negative feedback in the carbon-silicate geochemical cycle, i.e., plate tectonics and vulcanism (Kasting, 1989). This same feedback mechanism implies that an Earth-like planet could remain habitable out at least to the orbit of Mars. Exceptions to planets as abodes for life, are satellites orbiting giant planets within the HZ and satellites outside the HZ (Williams et al., 1997), but nevertheless contain internal stable bodies of liquid water (Smith et al., 1979; Squyres et al., 1983), due to mechanisms such as tidal heating (Reynolds et al., 1987).

3. Modern Theories for the Origin of Life

How life may have originated on the Earth is unknown. Two potential pathways are that life originated independently on Earth, or that life was transported to the Earth from elsewhere. This latter process is known as panspermia (Arrhenius, 1908), and it is possible that life (i.e., microbes) could have been transported from Mars to Earth or vice versa (Melosh, 1988; Moreno, 1988). However, whilst panspermia is feasible to explain the emergence of life on Earth (Weber and Greenberg, 1985; Horneck, 1993; Parsons, 1996), an origin of life event is still required to occur somewhere. Modern theories of the origin of life on Earth in the most part reject the notion of panspermia and seek to explain how life could arise and evolved into what we see around us today. The theories focus on how biological precursors such as amino acids and nucleotides could be generated from the abiotic environment and how such molecules formed information templates.

3.1. THE OPARIN/HALDANE BREAKTHROUGH

The first modern theory of the origin of life was independently advanced by Haldane and Oparin (Fox, 1965; Oparin, 1938). They suggested that the seeds of life arose in space and the atmosphere in the form of various combinations of the so-called CHNOPS elements, under the influence of electrical discharges, radiation and other sources of energy (Miller et al., 1997). According to Haldane (Wells et al., 1934), this material accumulated in the seas until "the primitive oceans reached the consistency of hot dilute soup". In rapidly evaporating inland lakes and lagoons the soup thickened. In some areas, it seeped deep below ground, and emerged back in hot geysers. All these exposures and churnings induced many chemical modifications and interactions in the original material that was formed in the atmosphere, and thus life arose in this soup. Oparin (1938) suggested that the order of events in the origin of life was cells first, proteins second and genetics third because he observed that when a suitably oily liquid, perhaps similar to what was formed on the primitive Earth, was mixed with water, sometimes the oily liquid dispersed into small droplets which remained suspended in the water which resembled the structures of living cells. Haldane's hypothesis was based upon the work of Baly (reported in Wells et al. (1934)), who noted that under the influence of light, small quantities of sugars and nitrogen containing compounds were generated from water, carbon dioxide and ammonia.

3.2. HYDROTHERMAL VENTS AS ORIGIN OF LIFE CENTERS

Life on Earth may have arisen without relying on a surface water/atmosphere interface. An alternative energy source to surface based systems is provided in the form of geothermal energy at hydrothermal vents and/or hot springs or seepages (Bock and Goode, 1996; Cowan, 1999). Hydrothermal vents can be found at the bottom of the ocean, where magma (liquid rock) spills through the Earth's crust

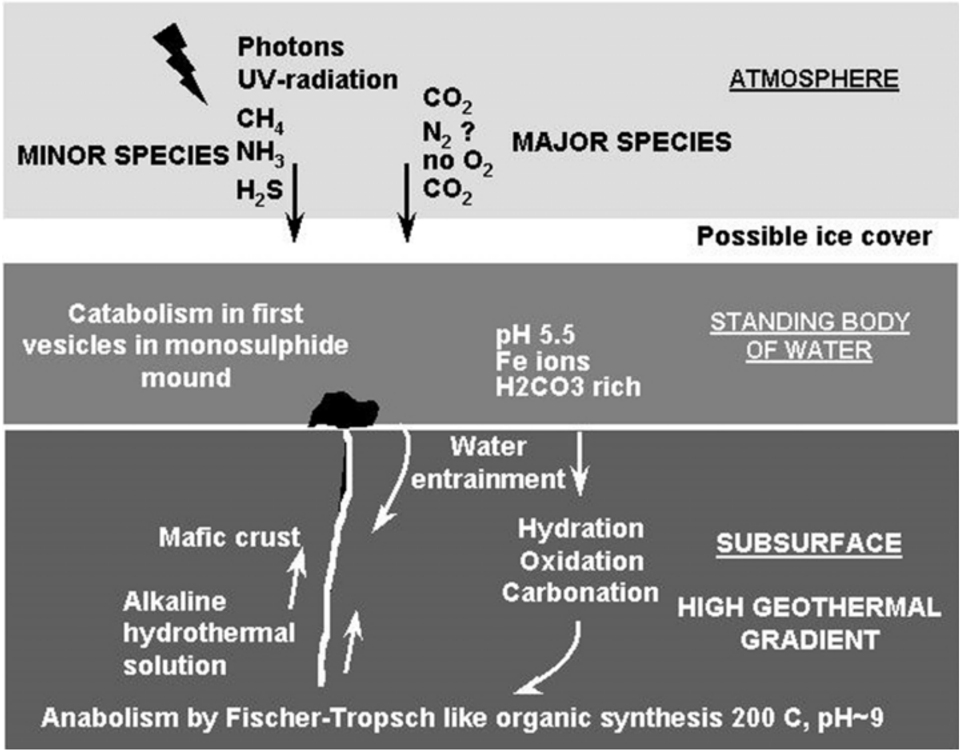

Figure 1. Steps along the hydrothermal origin of life as proposed by Macleod et al. (1994).

and reacts with the seawater. These geological features can be seen as contenders as sites for the origin of life because thermal, chemical and electrochemical energy is continuously focused there (Macleod et al., 1994) (Figure 1). Life could have emerged via iron sulfide membranes produced at such hydrothermal vents (Russell et al., 1993, 1998). These membranes would provide a number of features that are beneficial to life including catalytic sites and the fact that the hydrothermal solution would contain all the components necessary for synthesizing the building blocks of life (Shock, 1995, 1996). Although the idea of hydrothermal vents as origin of life centers has been challenged (Miller and Bada, 1988, 1991; Miller and Lazcano, 1995), laboratory simulations have synthesized amino acids under hydrothermal conditions (Shock, 1995, 1996; Hennet et al., 1992; Marshall, 1994; Imai et al., 1999).

3.3. THE CLAY MINERAL HYPOTHESIS

An alternative theory to account for the formation of information templates has been advanced by Cairns-Smith (1982), who proposed that self-perpetuating structures formed under some conditions by clays that may have acted as primitive information templates. Cairns-Smith (1982) argued that the simplicity and abundance of mineral structures makes such a relationship likely. The Cairns-Smith theory has the beginning of life as clay first, proteins second, cells third and genes fourth. Clay crystals directed the synthesis of protein molecules adsorbed to its surface. Later, the clay and the proteins learned to make cell membranes and thus became encapsulated in cells formed from such membranes. Thus the cells contained bits of clay that performed the crude functions of the DNA in modern day cells. Then a clay containing cell made the discovery that RNA was better genetic material than clay. As soon as RNA was invented, the cells using RNA had an immense advantage in precision during replication over cells using just the clay. Clay based life then became over run by RNA based life. Laboratory experiments have shown that clay catalyzed glycine and diglycine oligomerizations are possible (Bujdak and Rode, 1996). An alternative to a clay as substrate might be minerals (Arrhenius, 1984).

3.4. IRON PYRITE

Wächtershäuser (1988b) has speculated that life started out as a metabolic process, a cyclic chemical reaction that is driven by some source of energy taking place on the surface of a solid. In this case the surface is made up of pyrite, a metallic mineral made up of one part iron and two parts sulfur. Wächtershäuser suggests that pyrite can bind simple organic compounds and promote their joining together, and that the first cell may have contained a grain of pyrite enclosed in a primitive organic membrane. The cell could have reproduced if the pyrite grain grew a new crystalline bud that became encompassed in its own membrane and broke free. This theory has been challenged on thermodynamic and kinetic grounds (de Duve and Miller, 1991), although many of the criticisms have been addressed (Wächtershäuser, 1994). Thus Wächtershäuser (1988a) presents a metabolism first, surface based model. One of the key differences between the model of Wächtershäuser (1988b) and Russell et al. (1993) is that in the latter theory, although a central role for FeS is envisaged, instead the reducing power is provided by hydrothermal hydrogen.

3.5. AN RNA WORLD – THE ORIGIN OF INFORMATION TEMPLATES AND THEIR REPLICATION

The discovery that DNA was the genetic material (Watson and Crick, 1953a, 1953b) caused a rethink of the origin of life scenario proposed by Oparin/Haldane. The bases which make DNA can be divided into two sets, the purines and pyrimidines, both of which must have been present in the pre-biological environment for life to have arisen. Crick argued that DNA could not be the original "genetic unit" because DNA required proteins to replicate, and if there were no proteins around at the "origin of life" to help replicate the DNA, then how could DNA be replicated? This is the chicken and the egg paradox – which came first the chicken or the egg? Further, Crick suggested that ribonucleic acid (RNA), which is chemically similar to DNA, except that T is replaced by U, might have been the original genetic material, and that the RNA, besides containing all the genetic information, might also have acted as an enzyme, and in doing so promote its own self-replication (make copies of itself). The term “RNA world” was coined by Gilbert (1986), and has been used to refer to such a hypothetical time in the evolution of Earthly life. This idea led Eigen (1979) to reverse the order of events in the origin of life; a self-replicating RNA molecule at the very beginning of the information phase of life, proteins appearing soon afterwards to build with the RNA a primitive form of the modern genetic apparatus, and cells appearing later to allow the whole process to occur in a defined volume.

One of the primary tests if the idea of an RNA world was to succeed must be that RNA should not only be able to carry information but also act as an enzyme to replicate itself. Cech (1981) found certain RNA molecules that have enzymatic activity of one sort or another. These molecules can cut themselves in specified places and are called ribozymes. Thus the discovery of ribozymes removed one of the main objections to the “RNA world” hypothesis – that RNA cannot itself act like an enzyme (Cech, 1993). Indeed primitive sequences may have been only 30 to 60 bases long and the oligopeptides they encoded only 10 to 20 amino acids long. In the laboratory, under prebiotic conditions, short RNA sequences can be formed, roughly two to six bases in length. Comparisons with modern day metabolism and replication between different organisms led Benner (1988), and Benner et al. (1989) to propose that the breakthrough organism used DNA as its genetic material. One half of the genes may have been to do with translation (Loomis, 1988). Li (1994) found that palindromic duplex-like oligonucleotides 24 monomers long were able to self-replicate.

There is also difficulty reconciling the RNA world with the idea of RNA arising from a primordial soup. Some of the building blocks of RNA are very difficult to synthesize under prebiotic conditions including the ribose sugar of its backbone. Whilst purines are relatively easy to synthesize under prebiotic conditions, the synthesis of pyrimidines from simple precursors gives very low yields. Although a concentrated urea solution-such as might have been found in an evaporating lagoon or in pools along drying beaches on the early Earth, might yield pyrimidines in greater amounts than previously thought (Robertson and Miller, 1995a, 1995b). However, perhaps the greatest problem with pyrimidines is not their synthesis but the difficulty in attaching them to a sugar molecule to form the basic building block of the nucleic acid. It may be more than likely that RNA itself was not the first genetic material, but arose later on from some other precursor (Kolb et al., 1994). Another alternative that has been proposed is a peptide nucleic acid (PNA), which consists of a peptide backbone to which nucleobases are attached. PNA will bind to deoxyribonucleotides according to Watson-Crick base pairing. Chemically, PNA bridges the gap between protein and nucleic acids. PNAs can carry genetic information, but the backbone is protein.

4. Recreating the Conditions under which Life Originated

The Oparin/Haldane hypothesis would require that the building blocks of life be synthesized from components found on early Earth, this then is one of the crucial tests of the theory. Can we recreate this step in the laboratory? Unfortunately, the composition of the atmosphere at the time life originated is unknown. Miller (1959) argued that the primitive atmosphere was hydrogen (H_2) rich (reducing) and thus composed mainly of carbon dioxide (CO_2), water vapor (H_2O), hydrogen (H_2), ammonia (NH_3) and methane (CH_4). In a series of pioneering experiments Miller (1959) showed that when such gases were mixed in a pressure vessel and electricity sparked into the vessel (to simulate lightening) many organic compounds formed, including amino acids (which make up proteins).

Chyba (1991) argued that tholins may also have been present on the early Earth. Analysis of tholin showed that it consisted of a rich collection of organic molecules, including the constituents of proteins (such as amino acids) and nucleic acids, and thus these molecules may have provided a significant source of material for origin of life events. Certain terrestrial bacteria can use this material as a nutrient source (Stoker et al., 1990).

4.1. WAS THE EARTH'S EARLY ATMOSPHERE REDUCING OR NON-REDUCING?

Many of the origin of life theories discussed so far were in some respect formulated on the premise that the atmosphere of the early Earth was rich in hydrogen. However, laboratory experiments and computer models of the ancient atmosphere suggest that UV-radiation from the Sun, which is today blocked by ozone, would have destroyed hydrogen-based molecules in the atmosphere, such as the ammonia and methane liberating free hydrogen. The hydrogen, because it is light (16 times lighter than molecular oxygen) would have been lost to space. In this case the major component of the atmosphere would have been carbon dioxide and nitrogen that would have been disgorged during volcanic eruptions. Also, the high concentration of carbon dioxide coupled with water vapor would have led to a large greenhouse effect that caused the surface of the Earth to be near boiling point – although many bacteria have been found which thrive in water with temperatures above 100 °C. The reducing atmosphere may still have been present because smoke and clouds from the volcanic eruptions could have shielded chemicals like methane and ammonia from the harmful UV-radiation.

4.2. EXOGENOUS DELIVERY AND IMPACT SYNTHESIS OF ORGANIC MATERIAL

An alternative source of prebiotic reactants to primordial Earth and Mars is delivery by the impact of comets and or asteroids containing organic material (Owen and Bar-Nun, 1995) or synthesis during the impact event (Chyba and Sagan, 1992;

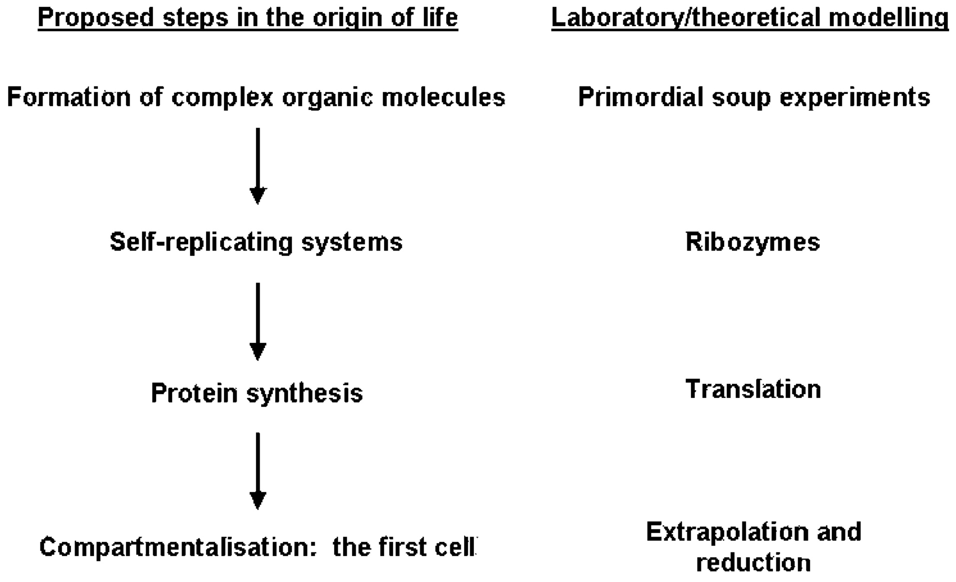

Figure 2. Schematic representation of the steps thought to be involved in the origin of life. Compartmentalization, i.e., membranes may have evolved separately. Theoretical simulations and laboratory experiments have been used to model each stage.

McKay and Borucki, 1997). Amino acids have been found in meteorites known as carbonaceous chondrites, which are thought to account for about 5 percent of the meteorites that crash into the Earth. Chondrites also contain hydrocarbons, fatty chemicals and alcohols that may have provided some of the chemicals which formed the membranes of primitive cells.

5. Towards a Grand Unified Theory – A Double Origin of Life Event

The Cairns-Smith theory requires a double origin of life event, much like the theory advanced by Russell and Hall (1997). First the evolution of a cell like structure followed by the incorporation of nucleic acids, whereas both the Oparin/Haldane and the Eigen theories were presented as single-origin of life events. Oparin/Haldane places primary emphasis on metabolism and barely discusses replication. Eigen places primary emphasis on replication and foresees metabolism falling into place rapidly as soon as replication is established. Dyson (1989) suggested that, “the Oparin [and Haldane] and Eigen theories make more sense if they are put together and interpreted as the two halves of a double-origin theory”. In essence Oparin/Haldane described the first origin of life event and Eigen the second (Dyson, 1985). Dyson (1989) sums up this idea with his usual clarity, “roughly speaking, Cairns-Smith equals Oparin plus Eigen plus a little bit of clay”. All three theories may turn out to contain essential elements of the truth (Figure 2).

de Duve (1991) also rejected the "RNA world" hypothesis as too complex. de Duve (1991) revisits the ideas of Oparin and Haldane, namely, that life originated with a kind of primitive metabolism. In particular de Duve (1991) argued that random chemical reactions on the early Earth would have produced a variety of oligopeptides along with other fragments, and that these compounds would have had a variety of enzymatic/catalytic properties, which means that they have the power to guide chemical reactions along non-random pathways. Eventually a network of interrelated catalysts and reaction products would begin to rise above the background "noise" thus providing a form of natural selection, but without genetics.

Benner (1988) considers the origin of life was composed of three episodes, the RNA world, a transitional stage in which the organism contains a messenger RNA that directs the synthesis of a protein required for its own replication. This organism may have used DNA for the storage of genetic information. This then lead to the emergence of a progenote, that led to the last common ancestor of life that we see today. The breakthrough organism may have had to have the following traits; biosynthesis of porphyrins, RNA cofactors, redox reactions, transmethylation, carbon-carbon bond formation, and an energy metabolism based on phosphate esters.

6. Mars as an Origin of Life Laboratory

One of the main problems with investigating the origin of life on Earth is the continuous reworking of the surface, which has destroyed any geological traces of an origin of life event. In addition there is no direct record of the composition of the primordial atmosphere. Possible clues to the origin of life might not be found on the Earth at all, and one of the focuses to solve this problem has turned into the new science of astrobiology. There are at least three places in the Solar System where possible clues to how life originated might be found; these are Mars (Hiscox, 1999a), Europa (Hiscox, 1999b) and Titan (Hiscox, 2000).

Estimates from the cratering record on Mars would indicate that geological processes were not so active on Mars after 3.8 Ga because many of the craters formed during the heavy bombardment still remain (Hartmann, 1973). Therefore evidence for the origin of life on Mars might still be found within the geological record of the planet (McKay, 1997). As on Earth, how life arose on Mars, if at all, is unknown. The problem and perhaps the solution to finding life on Mars has been eloquently expressed by McKay and Stoker (1989) "The critical unknown in gauging the possibility of the origin of life on Mars is how long clement conditions prevailed after the first occurrence of liquid water on the Martian surface".

6.1. EVIDENCE FOR LIQUID WATER ON MARS

Detailed studies of the images of the surface of Mars taken from orbit by Mariner 9, Viking Orbiters 1 and 2 and Mars Global Surveyor have provided convincing evidence that liquid water was once present on Mars (Baker, 1982; Carr, 1987, 1996). Ancient Mars was certainly warmer and wetter and its atmospheric pressure considerably higher than at present. From a biological perspective, there were many similarities between early Earth and early Mars (McKay and Stoker, 1989). This, combined with the prospect that the clement conditions on primordial Mars could have existed over time scales comparable to the origin of life on Earth, has led to the idea that life may also have arisen on Mars (Davis and McKay, 1996). Perhaps the strongest evidence that liquid water once flowed freely across the surface is the existence of dry river channels. Ancient Mars may also have had large, ocean-sized bodies of water (Helfer, 1990). For liquid water to have been stable would suggest that the atmosphere must have been denser in order to provide sufficient greenhouse warming (McKay and Davis, 1991). However, whether ancient Mars was "warm and wet" or "cold and icy" is unknown (Squyres and Kasting, 1994).

Most of the SNC meteorites date from 1.3 billion years ago, and therefore have the characteristics of Mars at that time (McSween, 1994). Analysis of these meteorites suggests that Mars formed with a larger fraction of water than the Earth (Watson et al., 1994), supporting the theory that early Mars had substantial water (Karlsson et al., 1992). If liquid water was once stable on the surface of Mars and the Martian atmosphere was of a similar composition to early Earth's, then synthesis of organic molecules via an organic soup model may have been possible. Alternatively, prebiotic synthesis may have occurred around hydrothermal vents (Russell et al., 1997, Russell and Hall, 1999); evidence suggests that Mars was once, and may still be, volcanically active. There seems adequate time on Mars for life to have originated and evolved into a protocell, yet no life is present on the surface of Mars. What may have happened to such life?

6.2. THE FATE OF LIFE ON MARS IS LINKED TO THE STABILITY OF WATER

The atmosphere of present day Mars is much less dense when compared to early Mars. A number of mechanisms may have removed much of the atmosphere of ancient Mars, including impacts, spluttering and the formation of carbonates. As a result the atmosphere was lost, so the planet cooled and the amount of UV radiation reaching the surface increased (Cockell et al., 2000). The potential origin and evolution of life on Mars has been linked to the stability of liquid water and several epochs have been defined (Friedmann and Koriem, 1989; McKay and Davis, 1991; McKay et al., 1992; Wynn-Williams, 1999) (Figure 3). First, as the temperature and humidity levels decreased, selection started for organisms that were tolerant of low temperatures and dry conditions. Organisms dependent on higher temperatures or aquatic environments with a surface interface became extinct. Second, with deterioration of the environment, the surface became uninhabitable. Cold-

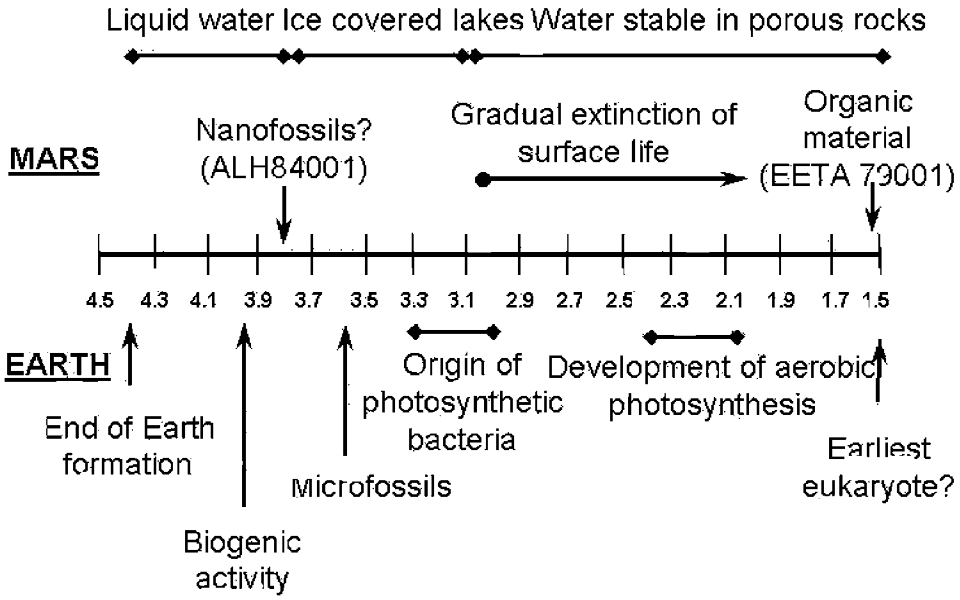

Figure 3. A comparison of the known steps in the origin and evolution of life on Earth with potential stages on Mars. The evolution of life on Mars has been linked to the stability of liquid water.

adapted organisms withdrew to protected niches under the surface or at the bottom of frozen lakes, where environmental factors still maintained conditions for life. Third, following further cooling even cold-adapted organisms living in protected areas existed at physiological limits. Further deterioration of the environment would have resulted in the extinction of life at the surface, most likely due to lethal levels of UV-radiation (Sagan and Pollack, 1974; Cockell, 2000). Extant (living organisms) such as chemolithotrophs might still be located below the martian surface, provided liquid water was stable (Boston et al., 1992). Evidence suggests that water may have been present on Mars in the near past (Malin and Edgett, 2000) and that water ice might be present near the surface of Mars in mid-latitudes (Mustard et al., 2001). Although there is no conclusive evidence for water on the surface of present day Mars, water might exist several kilometers below the surface (Fogg, 1999).

6.3. MULTIPLE ORIGIN OF LIFE EVENTS ON MARS MIGHT HAVE BEEN POSSIBLE

The penetration of the thermal wave of temperatures below 273 K was almost certainly not uniform across the surface of Mars; hence some parts of Mars may have become frozen before other parts. The formation of ice would have effectively separated the net transport both vertically and horizontally between surface dwelling and underground ecosystems. Also, the absence of plate tectonics on Mars

TABLE I

Estimated ages of the Martian plains, and the equivalent development of life on Earth, and hence possibly on Mars

Plains region	Age in 10^9 years		Stage of life on Earth (relative to best estimate)
	Best estimate	Range	
Mare Acidalium	1.2	0.2–1.7	Increase in diversity
Sinai Planum	1.4	0.4–3.0	Origin of eukaryotes
Utopia Planitia	1.8	0.6–2.3	Youngest detrial uraninities
Noachis Planitia	2.5	0.9–3.6	Oldest heterocyst like cells
Amazonis Planitia	2.8	1.0–3.7	As below
Syrtis Major Planum	2.9	1.2–3.7	Diversification of anaerobic prokaryotes
Chryse Planitia	3.0	1.2–3.8	Oldest stromatolites
Lunae Planum	3.5	1.7–3.8	Oldest fossils
Hellas	3.8	2.9–3.9	Earliest biogenic activity. Life on Mars?ALH84001)
Hesperia Planum	3.9	3.0–3.9	Origin of life on Earth

Note: Shaded area represents the time at which the climates of Earth and Mars may have been similar.

might have resulted in the formation of two distinct reservoirs of water (Clifford, 1993). Hence, there exists the exciting possibility of both spatial and temporal distribution between different water sources and putative ecosystems. The differences in freezing over Mars presumably progressing from pole to equator may have preserved organisms that were at different stages of development, perhaps from protocells to unicellular life, and evidence of this might be found on present day Mars. Table I shows the different estimated ages of the Martian plains. Given their geographical distribution, any remains of life could possibly be preserved at different stages. Hesperia Planum, the oldest plain, is situated approximately 20° south of the equator and might therefore have been one of the last places to freeze, and thus may contains traces of the most developed putative Martian organisms. The polar caps, which have been suggested as sites of interest for exobiological exploration (Cockell, 1995), might contain the oldest remnants of Martian life (Clifford et al. 2000).

7. Searching for Extinct or Extant Life on Mars

The problem is that discovering evidence for the past or present existence of life on Mars is likely to require the recognition and associative capabilities of the human mind. Even for a human explorer, the task will be no easier or less time consuming than was the search for traces of proterozoic life on Earth (Walter, 2000). Indeed the search for life on Mars may be technologically more demanding than anything that can be done with low cost unmanned robots.

Various robotic sample return missions have been proposed ranging from a 1994 NASA study at some $9 billion to a more modest Pathfinder/Beagle 2 hybrid for perhaps $0.5 billion. The idea is to return a sample of Mars (preferably from as deep below the surface as possible) to the Earth for analysis in terrestrial laboratories. However, returning a single sample to the Earth, or even several samples from the same location is statistically unlikely to provide unequivocal evidence of a former microbial community. A transect across a likely sedimentary plain is required, as for assessment of biological communities on Earth. Moreover, interpreting what samples tell us about ancient Mars is not without difficulties. Witness the debate over ALH84001. The original claims about ALH84001 centred on four pieces of evidence, none of which suggested life, but when taken together the evidence could be interpreted as indicative of life (McKay et al., 1996). However, whilst analysis of SNC meteorites suggests that conditions on ancient Mars were more clement (Karlsson et al., 1992), claims that some show evidence of fossilized life have been disputed, e.g., Bada et al. (1998) (for review see Grady et al., 1999).

Several sites have been selected on Mars, which may harbour traces of ancient Martian life (Farmer et al., 1995). These include polar regions (Cockell, 1995), regions of large standing bodies of liquid water (Helfer, 1990), evaporite deposits (Rothschild, 1990, 1995) and hydromagnesite deposits (Russell et al., 1999). If organic matter such as amino acids existed on Mars some 3.5 Gyr ago, then provided such material is preserved below the surface oxidizing layer, traces might still remain (Kanavarioti and Mancinelli, 1990). Indeed based upon the estimate of the amino acid, aspartic acid, racemization on Mars, Bada (1995) suggested that nucleic acid information might also be preserved. Ice covered lakes on Mars which may have persisted during times of climatic hostility to life would increase the probably of amino acids being preserved until present day (McKay and Davis, 1991). Analogous environments on the Earth, which resemble various time points on Mars, are being explored with regard to their exobiological potential, and these include Antarctica (Wynn-Williams, 1999) (Figure 4). In the Antarctic Dry Valleys, organisms such as cryptoendoliths (Figure 5), have been characterised which exist at the edge of extinction, similar organisms may have been present on Mars at various epochs. A fossil pigment record of molecules involved in UV protection and photosynthesis might still remain.

Figure 4. Several sites on Earth are being used as analogue environments of Mars, and these include Antarctica, where pools of liquid water remain covered in ice throughout the whole years, and microbes exist in rock profiles in the Antarctic Dry Valleys (pictured). (Courtesy Jim Johnson.)

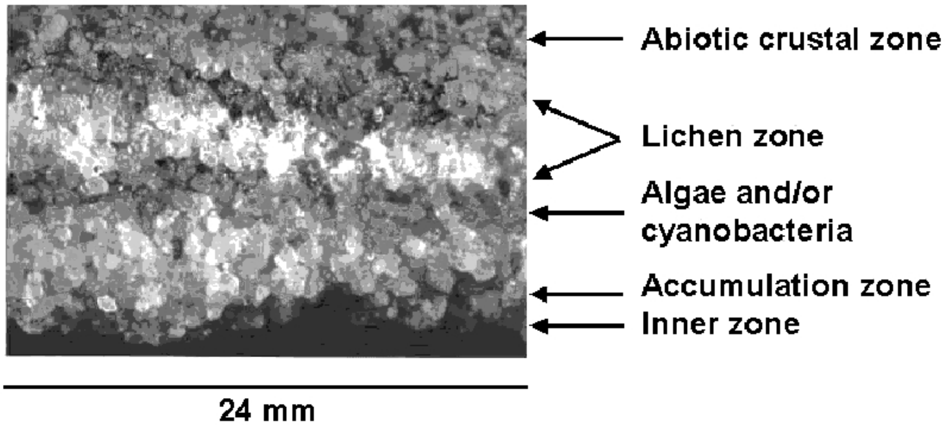

Figure 5. A vertical profile of an endolithic community in sandstone from East Beacon, Antarctica, consisting of various zones (indicated). (Taken from Newton et al., 2000.)

8. Robotic Versus the Human Exploration of Mars

Robot space probes and landers can carry a specific and diverse range of experiments and equipment designed to explore the many different geologic and chemically distinct regions of the surface of Mars. Although probes that are capable of performing robotic exploration of remote and difficult locations on Earth as well as on other planets are very cost effective in terms of the results obtained, their capabilities are not without limitations (Bock and Goode, 1996). On Earth the principle advantage of using robotic probes for exploration is that they can be sent into environments and locations that are extremely hostile and dangerous, or even lethal, for humans. For example, robotic probes are routinely used for exploring the abyssal ocean deeps and mid-oceanic spreading ridges. In surface environments robotic rovers have been developed for use in similarly hostile locations – the collection of gas samples within active volcanic calderas for example. Away from Earth, on Mars or any other terrestrial planet or satellite, the cost effectiveness of robot exploration versus human exploration, and the site to be explored are the key factors. This is because the life support requirements for the crew on a manned expedition add immensely to the mission cost and complexity without necessarily adding to the science capabilities (at least for surface science). Also, whilst rovers are adequate for exploring the surface and sub-surface of Mars (Newsom et al., 2001), robotic exploration is probably unsuitable for deep subsurface exploration where in situ construction of coring and sample machinery is required.

Anything more than a brief Apollo-like stay on the Martian surface will call for at least some form of temporary or semi-permanent habitation and life support system (Meyer and McKay, 1989). Over the past 40 years or so quite a wide range of possibilities has been examined (Von Braun, 1971, 1991; Zubrin and Weaver, 1995). Each of the ideas proposed has been designed to offer a particular advantage or advantages of one kind or another for operation on Mars, but many also suffer from adverse constructional, technological and economic problems. This problem of securing the best possible trade-off between the complex requirements of habitable bases or small-scale settlements on Mars has no unique solution. Given the present stage of our knowledge as to the distribution and availability of local resources on Mars it would be difficult to achieve anything like an optimal mission scenario. However, over the next two decades the robotic exploration of Mars from orbit and on the surface is likely to remove much, if not all, of this knowledge deficit (Farmer, 1999; Carr and Garvin, 2001). For example, Mars Odyssey will help determine the amount of radiation that humans would be exposed to on Mars. The benefits will be that even the earliest manned landings on Mars are likely to be able to exploit local resources to a worthwhile extent (Boston, 1988).

Having a crew also imposes critical limits on the time that can be spent exploring the surface of the planet. In many cases, with an unmanned robotic probe, it has proved possible to extend the mission time well beyond that originally planned. From this point of view, it might seem that there could be no justifiable reason for even considering sending humans to land on Mars for the purpose of scientific exploration. Most of the total budget for the mission would be spent on human life support and no more would be expended on scientific investigation than would be the case for a much lower cost unmanned robot exploration mission. Unless there is some overriding need that can only be fulfilled by a human presence on Mars, manned missions to the planet would certainly seem to offer too little science at too high a cost. However, this picture is deceptive in a number of ways, there are valid reasons – even for conducting purely scientific research – why it could be desirable to send human explorers to Mars (Boston, 1996, 1999).

8.1. WHY HUMAN EXPLORATION MAY BE NECESSARY

It is perhaps in the search for life on Mars that human exploration may be of particular significance (Farmer, 1999). At the present time there are many uncertainties regarding our abilities to detect and recognise evidence of life, as distinct from the presence of biogenic molecules, through the use of robotic surface explorer and analysing vehicles. Although several sophisticated techniques are now being considered and developed (Bada, 2001). For example, Raman spectroscopy should allow the differentiation between biomolecules and minerals associated with living organisms (Edwards and Newton, 1999; Newton et al., 2000; Wynn-Williams and Edwards, 2000). A rover scooping the surface seems to have had only a very low probability of discovering the presence of life even where it was actually known to exist. Even a percussive mole or a shallow drill at a single site has a limited chance of detecting biomolecules, although a long transect with several penetrations with a rover would increase the statistical chances of success. From such experiments it can be readily appreciated that the detection of any form of life at the microbial scale on Mars is going to pose considerable difficulties. Quite apart from the fact that recognition of Martian organisms may not be easy. This was certainly the case with the Viking landers, where two of three experiments assumed terrestrial type surface ecosystems were operating on Mars (Horowitz, 1986; Taylor, 1999), which with the benefit of hindsight was unlikely.

Although it now seems almost certain that early in its history Mars was both warmer and wetter than we previously believed it cannot be assumed that even if life was abundant there circa $\sim$3.8 billion years ago it will be an easy matter to discover evidence for the existence of any form of life on Mars so long ago. Although we possess fossil evidence for microbial life on the Earth back to almost four billion years ago, discovery of this morphological evidence was neither easy nor was it achieved rapidly. Only on the basis of many years of accumulated geologic knowledge were we able eventually to find and recognise the earliest traces of terrestrial life (Walter, 2000). Even now discovering additional evidence of the first traces of ancient terrestrial life remains a difficult and time-consuming task (Walter, 2000) and the search for relict biomolecules is more likely to be productive than a morphological search.

The case for the robot search for life rests on argument is that the relatively low mission costs for unmanned exploration will permit very large numbers of missions. Perhaps one or two orders of magnitude greater than possible for manned expeditions – to be flown and that this increases the probability that at least one of them will make the seminal discovery. Current estimates for a human Mars mission are around $40 billion – which includes technology development (Zubrin and Wagner, 1996). This is around four times as much as a sophisticated sample return but considerably less than the International Space Station (Zubrin, 1998). Life support considerations aside, humans are inherently more mobile and versatile than a rover. Humans have the ability to dig in both vertical (i.e., below the surface) and horizontal directions (into a cliff face) whereas a robot would have to be specifically designed and programmed to do these tasks and follow through with moles or drills. Traces of life on Mars, if they are to be found, based on current best estimates, are likely to be at least 10 meters below the surface (McKay, 1997). This would require a large robotic craft to drill down to this depth (or an Beagle 2 type mole penetrator). Several technologies have been proposed to accomplish reaching depths of 600 m and 3 km using robotic missions (Mancinelli, 2000). However, implementation of this technology may be problematic and subsurface drilling to depth would be more successful if humans were present to troubleshoot and also assemble a large borer from individual segments, this is after all how it occurs on the Earth.

9. Summary

Laboratory experiments have shown that the building blocks of life can be synthesized from compounds thought to be present on early Earth, whether in surface lagoons or around hydrothermal vents. In addition, comparisons between different organisms, and the discovery of billions of years old microfossils, have provided clues as to how life originated on the Earth and how life evolved from a self-replicating molecule to a cell. This origin of life event(s) may have occurred on ancient Mars, and biogenic remnants of this time might still remain. Searching for these traces is problematic to say the least, and Walter (2000) has rather succinctly summed up why humans maybe better at exploring Mars than robots, “There is a compelling argument that while robots can be made fairly smart, we are a great deal smarter and can achieve much more”.

References

Arrhenius, G.: 1984, in C. Wickramasinghe (ed.), *Fundamental Studies and the Future of Science*, University of Cardiff Press, Cardiff, pp. 301–319.

Arrhenius, S.: 1908, *Worlds in the Making*, Harper and Row, New York.

Bada, J. L.: 2001, *Proc. Natl. Acad. Sci. USA* **98**, 797–800.

Bada, J. L. and McDonald, G. D.: 1995, *Icarus* **114**, 139–143.

Bada, J. L., Glavin, D. P., McDonald, G. D., and Becker, L.: 1998, *Science* **279**, 362–365.

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

Benner, S. A. and Ellington, A. D.: 1988, *Nature* **332**, 688–689.

Benner, S. A., Ellington, A. D. and Tauer, A.: 1989, *Proc. Natl. Acad. Sci. USA* **86**, 7054–7058.

Bock, G. R. and Goode, J. A. (eds.): 1996, *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, John Wiley & Sons, Chichester.

Boston, P. J.: 1988, in D. B. Reiber (ed.), *The NASA Mars Conference*, Vol. 71, American Astronautical Society, Univelt, Inc., San Diego, pp. 487–507.

Boston, P. J.: 1996, in C. R. Stoker and C. Emmart (eds.), *Strategies for Mars: A Guide to Human Exploration*, Vol. 86, American Astronautical Society, Univelt, Inc., San Diego, pp. 327–361.

Boston, P. J.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 105–112.

Boston, P. J., Ivanov, M. V., and McKay, C. P.: 1992, *Icarus* **95**, 300–308.

Bujdak, J. and Rode, B. M.: 1996, *J. Mol. Evol.* **43**, 326–333.

Cairns-Smith, A. G.: 1982, *Genetic Takeover and the Mineral Origins of Life*, Cambridge University Press, Cambridge.

Carr, M. H.: 1987, *Nature* **326**, 30–35.

Carr, M. H.: 1996, *Water on Mars*, Oxford University Press, New York.

Carr, M. H. and Garvin, J.: 2001, *Nature* **412**, 250–253.

Cech, T. R.: 1993, *Gene* **135**, 33–36.

Cech, T. R., Zaug, A. J., and Grabowski, P. J.: 1981, *Cell* **27**, 487–496.

Chyba, C. and Sagan, C.: 1991, *Origins Life Evol. B.* **21**, 3–17.

Chyba, C. F. and Sagan, S.: 1992, *Nature* **355**, 125–132.

Clifford, S. M.: 1993, *J. Geophys. Res.* **98**, 10973–11016.

Clifford, S. M., Crisp, D., Fisher, D. A. et al.: 2000, *Icarus* **14**4, 210–242.

Cockell, C. S.: 1995, *J. Brit. Interplanet. Soc.* **48**, 355–364.

Cockell, C. S.: 2000, *Planet. Space Sci.* **48**, 203–214.

Cockell, C. S., Catling, D. C., Davis, W. L., Snook, K., Kepner, R. L., Lee, P., and McKay, C. P.: 2000, *Icarus* **146**, 343–359.

Cowan, D. A.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 37–48.

Davis, W. L. and McKay, C. P.: 1996, *Origins Life Evol. B.* **26**, 61–73.

de Duve, C.: 1991, *Blueprint for a Cell*, Portland Press, London.

de Duve, C. and Miller, S. L.: 1991, *Proc. Natl. Acad. Sci. USA* **88**, 10014–10017.

Dyson, F.: 1985, *Origins of Life*, Cambridge University Press, Cambridge.

Dyson, F.: 1989, *Infinite In All Directions*, Perennial Library, New York.

Edwards, H. G. M. and Newton, E. M.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 83–88.

Eigen, M. and Schuster, P.: 1979, *The Hypercycle: A Principle of Natural Self-Organization*, Springer-Verlag, New York.

Farmer, J., Des Marais, D., Greeley, R., Landheim, R., and Klein, H.: 1995, *Adv. Space Res.* **15**, (3)157–(3)162.

Farmer, J. D.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 58–65.

Fogg, M. J.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 66–72.

Fox, S. W.: 1965, *The Origins of Prebiological Systems and of their Molecular Matrices*, Academic Press, New York and London.

Friedmann, E. I. and Koriem, A. M.: 1989, *Adv. Space Res.* **9**, (6)167– (6)172.

Gilbert, W.: 1986, *Nature* **319**, 618.

Grady, M. M., Wright, I. P., and Pillinger, C. T.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 73–82.

Hartmann, W. K.: 1973, *J. Geophys. Res.* **78**, 4096–4116.

Helfer, H. L.: 1990, *Icarus* **87**, 228-235.

Hennet, R. J.-C., Holm, N. G., and Engel, M. H.: 1992, *Naturwissenschaften* **79**, 361–365.

Hiscox, J. A. (ed.): 1999a, *The Search for Life on Mars*, British Interplanetary Society, London.

Hiscox, J. A.: 1999b, *Astron. Geophys.* **40**, 2.22–2.26.

Hiscox, J. A.: 2000, *Astron. Geophys.* **41**, 5.23–5.24.

Horneck, G.: 1993, *Origins Life Evol. B* **23**, 37–52.

Horowitz, N. H.: 1986, *To Utopia and Back: The Search for Life in the Solar System*, W. H. Freeman, New York.

Imai, E.-i., Honda, H., Hatori, K., Brack, A., and Matsumo, K.: 1999, *Science* **283**, 831–833.

Kanavarioti, A. and Mancinelli, R. L.: 1990, *Icarus* **84**, 196–202.

Karlsson, H. R., Clayton, R. N., Gibson, Jr., E. K., and Mayeda, T. K.: 1992, *Science* **255**, 1409–1411.

Kasting, J. F.: 1989, *Palaeog.*, *Palaeoclimatol.*, *Palaeoecol.* **75**, 83–85.

Kasting, J. F., Whitmire, D. P., and Reynolds., R. T.: 1993, *Icarus* **101**, 108–128.

Kolb, V. M., Dworkin, J. P., and Miller, S. L.: 1994, *J. Mol. Evol.* **38**, 549–557.

Li, T. and Nicolaou, K. C.: 1994, *Nature* **369**, 218–221.

Loomis, W. F.: 1988, *Four Billion Years: An Essay on the Evolution of Genes and Organisms*, Sinauer Associates, Inc, Sunderland, MA.

Macleod, G., McKeown, C., Hall, A. J., and Russell, M. J.: 1994, *Origins Life Evol. B* **25**, 19–41.

Mallin, M. C. and Edgett, K. S.: 2000, *Science* **288**, 2330–2335.

Mancinelli, R. L.: 2000, *Planet. Space Sci.* **48**, 1035–1042.

Marshall, W. L.: 1994, *Geochim. Cosmochim. Acta* **58**, 2099–2106.

McKay, C. P.: 1991, *Icarus* **91**, 93–100.

McKay, C. P.: 1997, *Origins Life Evol. B* **27**, 263–289.

McKay, C. P. and Borucki, W. J.: 1997, *Science* **276**, 390–392.

McKay, C. P. and Davis, W. L.: 1991, *Icarus* **90**, 214–221.

McKay, C. P. and Stoker, C. R.: 1989, *Rev. Geophys.* **27**, 189–214.

McKay, C. P., Friedmann, E. I., Wharton, R. A., and Davis, W. L.: 1992, *Adv. Space Res.* **12**, (4)231–(4)238.

McKay, D. S., Gibson Jr., E. K., Thomas-Keprta, K. L., Vali, H., Romanek, C. S., Clemett, S. J., Chillier, X. D. F., Maechling, C. R., and Zare, R. N.: 1996, *Science*, **273**, 924–930.

McSween, H. Y.: 1994, *Meteoritics* **29**, 757–779.

Melosh, H. J.: 1988, *Nature* **332**, 687–688.

Meyer, T. R. and McKay, C. P.: 1989, *J. Brit. Interplanet. Soc.* **42**, 147–160.

Miller, S. L. and Bada, J. L.: 1988, *Nature* **334**, 609–611.

Miller, S. L. and Bada, J. L.: 1991, *Eos Trans. Amer. Geophys. Union* **72** (suppl.), 59.

Miller, S. L. and Lazcano, A.: 1995, *J. Mol. Evol.* **41**, 689–692.

Miller, S. L. and Urey, H. L.: 1959, *Science* **130**, 245–251.

Miller, S. L., Schopf, J. W., and Lazcano, A.: 1997, *J. Mol. Evol.* **44**, 351–353.

Mojzsis, S. J., Arrhenius, G., McKeegan, K. D., Harrison, T. M., Nutman, A. P., and Friend, C. R. L.: 1996, *Nature* **384**, 55–59.

Moreno, M. A.: 1988, *Nature* **336**, 209.

Mustard, J. F., Cooper, C. D., and Rifkin, M. K.: 2001, *Nature* **412**, 411–414.

Newsom, H. E., Bishop, J. L., Cockell, C. S., Roush, T. L., and Johnson, J. R.: 2001, *J. Geophys. Res.-Planets* **106**, 7713–7720.

Newton, E., Edwards, H. G. M., Wynn-Williams, D., and Hiscox, J. A.: 2000, *Astron. Geophys.* **41**, 5.28–5.30.

Oparin, A. I.: 1938, *The Origin of Life*, Macmillan, New York.

Overbeck, V. R. and Mancinelli, R. L.: 1994, *BioScience* **44**, 173–177.

Owen, T. and Bar-Nun, A.: 1995, *Icarus* **116**, 215–226.

Parsons, P.: 1996, *Nature* **383**, 221–222.

Reynolds, R. T., McKay, C. P., and Kasting, J. F.: 1987, *Adv. Space Res.* **7**, (5)125–(5)132.

Robertson, M. P. and Miller, S. L.: 1995a, *Nature* **375**, 772–774.

Robertson, M. P. and Miller, S. L.: 1995b, *Science,* **268**, 702–705.

Rothschild, L. J.: 1990, *Icarus* **88**, 246–260.

Rothschild, L. J.: 1995, *Adv. Space Res.* **15**, 223–228.

Russell, M. J. and Hall, A. J.: 1997, *J. Geol. Soc.* **154**, 377–402.

Russell, M. J. and Hall, A. J.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, The British Interplanetary Society, London, pp. 26–36.

Russell, M. J., Daia, D. E., and Hall, A. J.: 1998, in M. W. W. Adams, L. G. Ljungdahl, and J. Wiegel (eds.), *Thermophiles: The Keys to Molecular Evolution and the Origin of Life*, Taylor & Francis, Washington, pp. 77–126.

Russell, M. J., Daniel, R. M., and Hall, A. J.: 1993, *Terra Nova* **5**, 343–347.

Russell, M. J. Ingham, J. K. Zedef, V. Maktav, D. Sunar, F. Hall A. J., and Fallick, A. E.: 1999, *J. Geol. Soc.* **156**, 869–888.

Sagan, C. and Pollack, J. B.: 1974, *Icarus* **21**, 490–495.

Schidlowski, M.: 1988, *Nature* **333**, 313–318.

Schopf, J. W.: 1989, in J. L. Gould and C. G. Gould (eds.), *Life at the Edge*, Freeman, New York, pp. 7–23.

Schopf, J. W. and Parker, B. M.: 1987, *Science* **237**, 70–73.

Schwartzman, D., McMenamin, M., and Volk, T.: 1993, *BioScience* **43**, 390–393.

Shock, E. L.: 1995, *Amer. J. Sci.* **295**, 496–580.

Shock, E. L.: 1996, in G. R. Bock and J. A. Goode (eds.), *Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*, Wiley, Chichester, pp. 40–60.

Smith, B. A., Soderblum, L. A., Beebe, R., Boyce, J., Briggs, G., Carr, M., Collins, S. A., Cook II, A. F., Danielson, G. E., Davies, M. E., Hunt, G. E., Ingersoll, A., Johnson, T. V., Masursky, H., McCauley, J., Morrison, D., Owen, T., Sagan, C., Shoemaker, E. M., Strom, R., Suomi, V. E., and Veverka, J.: 1979, *Science*, **206**, 92-950.

Squyres, S. W. and Kasting, J. F.: 1994, *Science* **265**, 744–749.

Squyres, S. W., Reynolds, R. T., Cassen, P. M., and Peale, S. J.: 1983, *Nature* **301**, 225–226.

Stoker, C. R., Boston, P. J., Mancinelli, R. L., Segal, W., Khare, B. N., and Sagan, C.: 1990, *Icarus* **85**, 241–256.

Taylor, R. S.: 1999, in J. A. Hiscox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 3–17.

Von Braun, W.: 1971, *Space Frontier*, Holt, Rinehart and Winston, New York.

Von Braun, W.: 1991, *The Mars Project*, University of Illinois Press, Illinois.

Wächtershäuser, G.: 1988a, *Microbiol. Rev.* **52**, 452–484.

Wächtershäuser, G.: 1988b, *Syst. Appl. Microbiol.* **10**, 207–210.

Wächtershäuser, G.: 1994, *Proc. Natl. Acad. Sci. USA* **91**, 4283–4287.

Walter, M.: 2000, *The Search for Life on Mars*, Perseus Book Group.

Watson, J. D. and Crick, F. H. C.: 1953a, *Nature* **171**, 964–967.

Watson, J. D. and Crick, F. H. C.: 1953b, *Nature* **171**, 737–738.

Watson, L. L., Hutcheon, I. D., Epstein, S., and Stolper, M.: 1994, *Science* **265**, 86–90.

Weber, P. and Greenberg, J. M.: 1985, *Nature* **316**, 403–407.

Wells, H. G., Huxley, J., and Wells, G. P.: 1934, *The Science of Life*, The Waverley Book Company, Ltd., London.

Williams, D. M., Kasting, J. F., and Wade, R. A.: 1997, *Nature* **385**, 234–236.

Woese, C. R.: 1987, *Microbiol. Rev.* **51**, 221–271.

Wynn-Williams, D. D.: 1999, in J. A. Hicox (ed.), *The Search for Life on Mars*, British Interplanetary Society, London, pp. 49–57.

Wynn-Williams, D. D. and Edwards, H. G. M.: 2000, *Icarus* **144**, 486–503.
Zubrin, R. M.: 1998, *J. Brit. Interplanet. Soc.* **51**, 116–120.
Zubrin, R. and Wagner, R.: 1996, *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*, The Free Press, New York.
Zubrin, R. M. and Weaver, D. B.: 1995, *J. Brit. Interplanet. Soc.* **48**, 287–300.

Discussion

Mr. Horace Regnart: If there has been life in sufficient abundance at some time in the past on Mars, could that have had an effect on the atmosphere such that some kind of chemical signature was left that survives today?

Dr. Hiscox: I'm happy to be corrected as I'm not a chemist, but I don't think so. It may be possible to drill down below the surface and expose pockets of such gas, but the depths to which you would have to drill are those very depths at which you would find background amino acids that we would expect to find on Mars in any case, whether there was life present or not.

Mr. William Clarkson (University of Southampton): Given that the top 10 m or so of the surface of Mars is sterilised, wouldn't it be better to look in places where the sub-surface material has been brought to the surface, such as near an impact crater? That way you wouldn't have to dig.

Dr. Hiscox: Yes it would, but the problem is that the surface of Mars is driven by the wind, which will transport any superoxide or peroxide dust grains around the planet. Unless the meteorite crater is very, very new any organic material is going to be degraded. We must have pristine conditions. We are going to have to drill down or sideways, and the size of the drill will probably require humans to operate it.

Dr. Julian Osborne (University of Leicester): Why is it necessary to drill as deep as 10–100 m to avoid the superoxides, when UV radiation cannot penetrate to anything like that depth?

Dr. Hiscox: The problem is that because of the action of meteorites and so on, the regolith has been churned up to a depth of about 1 to 10 m, and the surface of Mars is effectively composed of these superoxides.

Dr. Andrew Coates (Mullard Space Science Laboratory, UCL): Beagle 2 has a mole and a grinder/corer – the latter will drill into rocks, so there is a sampling of the inside of rocks and further below the surface. Doesn't that give a chance of detecting life?

Dr. Hiscox: The mole on Beagle 2 won’t go down far enough, although it will prove the technology which is a good development.

Dr. Andrew Coates: And the grinder/corer will actually drill into at least the surface layer of rock, so you are not reliant just on the regolith.

Dr. Hiscox: No, you are not.

Mr. William Clarkson: Suppose life, or evidence for it, is found in a 2 billion year old rock. How can the possibility be ruled out that it is not the result of transfer from Earth?

Dr. Hiscox: You can rule it out in one way, and that is by phylogenetic analysis. If that life had the same chemistry as life on Earth, but its genetic material was arranged differently, then you could rule it out.