Part 1:

The Search for Evidence of Life on Mars

by the Mars Expeditions Strategy Group

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Focus

Did life ever exist on Mars? A multi-disciplinary group of scientists brought together by the National Aeronautics and Space Administration (NASA) is currently [i.e., 1996] developing a strategy to seek the answer to that question. When complete, this strategy will form the basis for NASA's future program of Mars exploration. This report is a statement of work-in-progress by the group to identify a systematic approach, using robotic space missions and laboratory analyses of samples returned to Earth, to understand the possible origin and evolution of life on Mars.

NASA is today conducting a series of robotic missions to Mars with the goal of understanding its climate, resources, and potential for harboring past or present life. The measurements to be made have in common the study of water and its history on the planet. The first mission to return to the surface of Mars since the Viking spacecraft in 1976 will be launched in December of 1996. Also this year, an orbiter will begin regional and global mapping of the surface, searching for sites potentially hospitable to life some time in the planet's past.

Hypotheses

The fundamental requirements for life as we know it are liquid water, an inventory of organic compounds, and an energy source for synthesizing complex organic molecules. Beyond these basics, we have yet to achieve consensus regarding the environmental requirements or the processes of chemical evolution that lead to the origin of life. Comparisons of sequences in living organisms suggest that the last common ancestor of life on Earth may have been a sulfur-utilizing bacterium that lived at high temperatures. This implies that hydrothermal environments were important in the early evolution of the biosphere. Given that hydrothermal systems have also been shown to be energetically favorable places for synthesis, some scientists believe that it was in such a location that life actually originated. However, others argue quite convincingly for a low-temperature origin of life.

Unfortunately for attempts to resolve this controversy, plate tectonics and extensive recycling of the crust have obliterated record of prebiotic chemical evolution on Earth. The story is, however, quite different for Mars. The absence of plate tectonics suggests that the Martian crustal record is much better preserved than that on Earth. The cratering record on Mars implies that vast areas of the Martian southern highlands are older than 3.8 billion years. Analysis of meteorites from Mars indicates that some highland terrains date back to the very earliest period of planetary evolution (~4.5 billion years), overlapping the period on Earth when prebiotic chemical evolution first gave rise to life. Thus, even if life never developed on Mars, any inventory of biogenic elements and organic compounds that may be preserved in the rocks of the cratered highlands will yield crucial information about the prebiotic chemistry that led to living systems on Earth.

Environments

The members of the Mars strategy group recommend that the search for life on Mars should be directed at locating and investigating, in detail, those environments on the planet that were potentially most favorable to the emergence (and persistence) of life. Three in particular can be cited for concentrated study:

(1) Ancient ground water environments: early in the planet's history, liquid water, regarded as prerequisite for life, appears to have been widespread beneath the surface and may have provided a clement environment for the origin of life. Intense energy was dissipated by impacts associated with the final stages of planetary accretion and, along with volcanism, could have created warm ground water circulation systems favorable for the origin of life. In this scenario, evidence for ancient habitats may be found in the heavily cratered terrains of the Martian highlands.

(2) Ancient surface water environments: also during early Martian history, liquid water was apparently released from subsurface aquifers, flowed across the surface, and pooled in low-lying regions. Solar irradiance would have provided biologically useful energy. During this period habitats may have been formed, with evidence of life preserved in water-lain sediments in the valley systems and basins found in the highlands.

(3) Modern ground water environments: life may have formed at any time, including recently, in habitats where subsurface water or ice is geothermally heated to create warm ground water circulation systems. In addition, life may have survived from an early epoch in places beneath the surface where liquid water is present.

Given our present uncertainty about the environmental conditions necessary for the origin of life, and our limited knowledge of the geologic history of Mars, we urge strongly that the investigation strategy emphasize sampling at diverse sites. It is specifically recommended that the implementation of the program of exploration of Mars be aimed at the study of a range of ancient and modern aqueous environments. These environments may be accessed by exploring the ejecta of young craters, by investigating material accumulated in outflow channels, and by coring.

Needed Investigations

In situ studies conducted on the surface of Mars are essential to our learning more about Martian environments and for selecting the best samples for collection. However, for the next 10 years or more, the essential analyses of selected samples must be done in laboratories on Earth. It is evident from studies of meteorites that it is difficult to predict the full suite of analytic techniques that will be needed to complete the analysis of returned samples. Further, based upon the results of Viking landers and analyses of Martian meteorites, markers of life are thought to be at low concentrations; and fossils, if present, are likely to be very small. Therefore, "high-precision" (i.e., sophisticated, state-of-the-art) analytical techniques must be used, such as those found in only the most advanced laboratories here on Earth.

We also believe that to achieve widely accepted confirmation of Martian life, all three of the following must be clearly identified and shown to be spatially and temporally correlated within rock samples: (1) organic chemical signatures that are indicative of life, (2) morphological fossils (or living organisms), (3) supporting geochemical and/or mineralogical evidence (e.g., clearly biogenic isotopic fractionation patterns, or the presence of unequivocal biominerals). These characteristics cannot be properly evaluated without the return of a variety of Martian samples to Earth for interdisciplinary study in appropriate laboratories.

Precursor orbital information must be obtained, as well, to select the best sites for surface studies. We can already say with reasonable certainty, however, that the ancient highlands represent a region of great potential, and that at least the initial focused studies should be performed there. Maps of surface mineralogy will be needed to enhance investigations within the highlands and enable searches elsewhere. This work begins with the launch of the Mars Global Surveyor (MGS) later this year. Additional measurements from orbit at higher spatial resolution are essential to identify productive sites (e.g., regions containing carbonates) at scales accessible by surface rovers. In addition, instruments capable of identifying near-surface water, water bound in rocks, and subsurface ice would greatly accelerate and make more efficient our search for environments suitable for life.

We have found it useful to consider the factors that lead to the fossilization and long-term preservation of microorganisms and key compositional indicators in rocks. Based on studies of the microbial fossil record on Earth, the long-term preservation of organic signatures is most favored within sedimentary environments where aqueous minerals precipitate rapidly from solution, entrapping organic materials within an impermeable mineral matrix. The best host minerals are those that have long crustal residence times by virtue of being chemically stable. In ancient rock sequences on Earth, organic materials tend to be found in association with a fairly restricted number of sedimentary precipitates, which include silica, phosphate, and carbonate. Preservation of polycyclic aromatic hydrocarbons within the carbonates of the Martian meteorite ALH 84001 indicates that such mineralization processes were an effective means for capturing organic materials in the early Martian crustal environment and, importantly, for preserving them for billions of years.

From these factors we judge that an implementation strategy for the initial phases of Mars exploration can already be affirmed:

> (1) For ancient ground water environments, a sample return mission can occur relatively soon, since the necessary precursor information for site selection is already available from existing orbital photogeologic data, including Mariner 9 and Viking imagery, or will be provided by Mars Surveyor orbiters in ’96, ’98[*] and ’01.
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> (2) For ancient surface water environments, orbital and surface exploration/ characterization should precede sample return because identification of extensive

[*] Due to the loss of the Mars ’98 spacecraft, data are not available from that mission.

areas of carbonates and evaporites is highly desirable. This implies the use of advanced orbital and in situ instruments for mineral characterization. Technologies that enable long-range surface exploration are also needed.

(3) For modern ground water environments, additional means for the identification of thermally active regions will be needed. Techniques for location of subsurface water (i.e., liquid and ice) are also needed.

Sample return missions will retrieve the most productive samples if they are supported by extensive searches, analyses, and collections performed by sophisticated rovers. These should be capable of ranges of 10s of kilometers in order to explore geologically diverse sites. The specific samples to be returned to Earth would be selected using criteria that increase the probability of finding direct evidence of life as well as the geological context, age, and climatic environment in which the materials were formed.

In order to retrieve scientifically meaningful samples, significant constraints must be placed on the way samples are handled during collection and return to Earth. We anticipate retrieving dry rocks and minerals for which mechanical preservation is a major factor; self-abrasion or shake-induced disintegration of the samples must be minimized. Almost certainly, the rocks will have been exposed already at the Mars surface so that packing can be accomplished using local Mars soils; individual containerization of different rocks might not be a strict requirement. For subsurface environments, where ices or brines are possible, sample materials must be handled in such a way that melting or evaporation of volatiles within the samples can be controlled. For volatile-rich samples, temperature control, individual containerization, and hermetic sealing to prevent mass loss or mass exchange are likely to be requirements. If extant life is found, even more stringent environmental controls may be required. For samples from all environments, preservation protocols must address the sensitivity of biogeochemical materials (organic compounds plus minerals containing the chemical elements H, C, N, O, S, and P) to material contamination and to thermal degradation.

Unmodified samples of the Martian atmosphere must also be brought back to Earth where they can be examined in our laboratories. The possibility of the origin and evolution of life on Mars must be fundamentally linked to the evolution of the atmosphere, through its contribution of biogenic elements and compounds (including water), through chemical reactions taking place at the atmosphere-surface interface, and through regulation of the planetary climate.

Although precise requirements for sizes or masses of samples require further evaluation, our preliminary recommendation is that individual rock samples should be on the order of at least 10–20 grams. Experience with planetary samples, including Martian meteorites, has amply demonstrated that a representative 10–20-gram rock sample can be divided effectively and distributed to state-of-the-art laboratories to accomplish all of the important measurements. Even though larger samples are desirable for certain types of studies, the Apollo lunar program taught us that a limited sample payload mass is more profitably expended on numerous small samples than on a few large ones.

To summarize, our science strategy is predicated on the execution of several (at least three) mission sequences of precursor orbital and roving elements together with selected retrieval of samples for detailed analysis in Earth laboratories. To achieve efficiencies of time and cost, sample selection and caching may occur at more sites than sample return. An endeavor of this nature involves a number of uncertainties and should be expected to encounter occasional setbacks. The overall structure and implementation of the program must be sufficiently flexible to accommodate these perturbations and to adjust to discoveries as it progresses.

Sample Quarantine

By long-standing international agreement, space-faring nations take measures to protect planetary environments against biological cross-contamination during space exploration missions. We assume that some level of sample quarantine will be included in mission requirements. We recommend that any sample quarantine and sterilization protocols be closely coordinated with plans for analysis of returned samples; and we urge that care be taken throughout the planning process to assure that trade-offs among quarantine, sterilization, and science goals are clearly understood before implementation plans are adopted. Even though sample quarantine probably will be conducted in a restricted-access facility, and some preliminary characterization of the samples will occur behind the quarantine barriers, we believe that the maximum value of the samples can be extracted only if the samples are made available to scientists in their individual, specialized laboratories. Therefore, we recommend that, if sample quarantine and sterilization become operational requirements, some provision be made so that sterilized samples can be released to outside research laboratories, with suitable controls, and at the earliest possible opportunity in the execution of the program.

Technology Requirements

Although this group of scientists has only recently begun to develop a road map for enabling technologies, we can already see several technology needs emerging:

(1) Long-range rovers capable of surviving from months to years on the Martian surface. Rovers must be capable of carrying a sophisticated battery of tools and instruments over distances of 10s of kilometers.

(2) Low-mass propulsion, power, and communications systems for landed elements (e.g., Mars ascent vehicles and rovers).

(3) High-spatial-resolution (orbital) remote sensing instruments. Spectrometers and radiometers are needed for mineralogy and detection of thermally active regions.

(4) In situ instruments, supported by sample preparation tools, able to identify aqueous minerals in rocks and relative ages of samples. A report by a NASA ad hoc working group on instruments for exopaleontology includes descriptions of promising techniques (Point Clear Exobiology Instrumentation Workshop, 13–17 May 1996; T. J. Wdowiak, D. G. Agresti, J. Chang, Eds.).

(5) Tools are needed for shallow excavation, coring to depth, rock and soil manipulation, and sample preparation. Tools must be lightweight and low power.

(6) Development of advanced terrestrial laboratory instrumentation.

These requirements for technology will be refined and additional technologies identified in the near future as the exploratory strategy unfolds. It is clear today, however, that development should proceed apace with long-lead technologies (e.g., instruments, rovers, propulsion systems).

Opportunities For International Collaboration

We view the exploration of Mars to be inherently an international undertaking. The strategy outlined above is well suited to, and likely to be dependent upon, foreign involvement. Participation by non-US scientists and agencies could range from participation in individual instruments to entire missions being sponsored abroad.

Human Exploration

The science strategy described above requires a series of robotic sample return missions. This series may continue until either:

(1) it has been conclusively shown that life existed on Mars at some time in the past; or

(2) the evidence for Martian life is ambiguous, but little progress is being made, or expected, through additional robotic sample returns. (We note that it is impossible to prove that life never arose on Mars.)

In the former case, the questions of life’s beginning, evolution, and possible survival to the present become prominent scientifically. In the latter case, we will inevitably have learned much more about the environments that existed throughout Mars’ history, but we will be hindered by lack of technology, lack of new ideas, or lack of resources. At present, we are encouraged in (1) above by the discoveries in Antarctic meteorite ALH 84001. In either case, a re-examination of the strategy will be necessary after analysis of the initial returned samples.

Exploration involving humans may be required at this decision point. If past life were to be demonstrated, the questions then asked would be more complex, requiring substantially larger amounts of data, a reconnaissance mode of exploration would no longer be sufficient, and the observational and analytical capabilities that could be provided by humans could be the more effective approach. If the data were still ambiguous, but promising, the need for human in situ capabilities could prove compelling. For example, if the search turns to locating and drilling for extant subsurface warm aqueous systems, the observational and manipulative skills of humans could be important. Thus, the perceived difficulties of making further progress could form the basis for a decision to conduct human scientific exploration of Mars. The questions raised by the discovery of evidence for past or present life on Mars could become so important that they provide much of the rationale for human exploration.

Whether human missions become practical and desirable either from the scientific perspective, or from other rationales, the robotic orbital, surface, and sample return program will provide important information to support human missions, through (1) characterization of the surface environment in which humans must establish their presence, such as the toxicity of dust, the availability of water, the radiation environment, and resolution of the forward/back-contamination issues; and (2) development and/or demonstration of technologies that would be used in human missions, such as Mars resource extraction systems, surface mobility, deep coring, and analytical instrumentation, among others.

Mars Meteorite Research

In addition to pursuing an exploration program focused on missions to the planet, we strongly endorse NASA's efforts aimed at increasing the number of Martian samples available for laboratory study through expanded support of the NSF/NASA/Smithsonian-sponsored Antarctic Search for Meteorites (ANSMET) program. Five Martian meteorites have been discovered through the US Antarctic program since 1977, and an additional sample has been documented (but not yet extensively studied) in the similar effort by Japanese Antarctic teams. For the US program alone, this corresponds to approximately one Martian meteorite per 1000 Antarctic meteorites collected, or one Martian rock per four seasons of meteorite collection. The Mars Expeditions Strategy Group encourages investigation of ways in which the productivity of ANSMET—measured in terms of the area searched each season—can be increased to allow the rate of discovery of Martian meteorites to be accelerated. Re-examination of the methodologies used to locate, document, and collect samples might allow such an increase in productivity without calling for an increase in the number of participants involved in the field collection effort. In addition, NASA should expand the resources applied to the laboratory processing, cataloging, and organically clean handling of Martian meteorites so that research relevant to the search for Martian life can be supported at a faster pace.

Methodologies used in the handling and study of meteorites from Mars are similar to those that will be applied to samples retrieved from Mars by spacecraft. Continued support of ANSMET and Martian meteorite research will assist directly in preparation for eventual Mars sample analysis. It is our view, moreover, that strong ties should be forged with other nations participating in meteorite searches (such as Japan) to further expand the effort. While we do not suggest that study of more meteorite samples will unequivocally answer the question of whether life ever existed on Mars, we have no doubt that analysis of a larger set of Martian meteoritic materials will enhance our understanding of the geological and possible biological history of the planet.

Mars Expeditions Strategy Group
26 September 1996