JPL Publication 01-7

Science Planning for Exploring Mars

Part 1: The Search for Evidence of Life on Mars
D. McCleese
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Part 2: Scientific Goals, Objectives, Investigations, and Priorities
R. Greeley
Arizona State University, Tempe, Arizona

Part 3: The First Returned Martian Samples: Science Opportunities
G. MacPherson
Smithsonian Institution, Washington, D.C.

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

July 2001

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Table of Contents

Foreword

This document is a collection of three white papers that capture the development of NASA's science strategy for exploring Mars using robotic spacecraft. These papers are products of three science working groups chartered by NASA between 1996–2001. The present collection captures the continuing refinement of NASA's vision of Mars exploration and the emergence of Mars as an international focus for space exploration. The white papers are also sources of science requirements that are levied on missions to Mars.

The strategy for exploring Mars described here is realized in a series of spacecraft that carry instruments judged by NASA and the science community to be likely to unlock the key questions relating to the origin and evolution of the planet and its potential for harboring life. Specific investigations are chosen, in part, based upon the extent to which they address questions of high priority described in the three white papers collected here. Central to those priority questions is whether water was ever persistent on the surface of Mars and whether, therefore, the planet was ever habitable. Simply stated, these questions are:

- When was water present on the surface of Mars?
- Did water persist at the surface long enough for life to have developed?
- How much and where was the water?
- Where did the water go that formed the fluvial features evident on the surface of modern Mars?

By following the history of water, robotic missions may find the environments and specific surface sites where life might have originated and evolved.

Mars Expeditions Strategy Group

Immediately following the announcement by McKay et al. (*Science* 1996 August 16; 273: 924-930) that the Mars meteorite ALH 84001 appeared to exhibit signatures of past life, NASA Administrator, Mr. Dan Goldin, asked a group of scientists to formulate a science strategy for exploring Mars. Explicit in Mr. Goldin's charge to the Mars Expeditions Strategy Group (MESG) was the challenge to create a strategy that would determine whether life had ever existed on Mars. MESG membership included some 20 scientists from biology, geology, and climatology, as well as several engineers and technologists. The group presented its strategic plan in the first of the papers reproduced here. In this plan, MESG outlined a program consisting of global reconnaissance and in situ measurements of the surface, followed by bringing samples of Mars to Earth. MESG also identified specific classes of surface sites for detailed study – ancient sites of groundwater, ancient sites of surface water, and modern sites of groundwater.

Mars Exploration Payload Analysis Group

In the course of planning and executing missions to Mars it became evident that another step of strategic planning was needed. The goals of the NASA's Mars Exploration Program needed to be more directly linked to specific investigations and then to measurements that can be made by science payloads aboard spacecraft or conducted in Earth-based laboratories. In response to this need the Mars Exploration Payload Analysis Group (MEPAG) created "investigation pathways" that link the program's strategic goals to specific prioritized measurements. Investigations are described by MEPAG in terms of measurement methodologies, together with instrument specifications such as spectral and spatial resolutions.

Mars Sampling Advisory Group

No investigation is more crucial to the strategy of MESG and to the investigation pathways of MEPAG than the analysis of Martian rock, soil, and atmosphere in the best laboratories on Earth. Indeed, the scientific value of sample analysis is such that this objective has emerged as the cornerstone of an international program to explore Mars. To elucidate the characteristics of early sample return, MEPAG formed a special sub-group. In the third paper, the MEPAG Mars Sample Advisory Group set forth the anticipated knowledge to be gained from the first returned samples. Sample return, because of its importance and the difficulty of achieving it, currently dominates much of the scientific and technological planning of the Mars Exploration Program.

Part 1:

The Search for Evidence of Life on Mars

by the Mars Expeditions Strategy Group

Chair: Dan McCleese

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.

(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

Part 2:

Scientific Goals, Objectives, Investigations, and Priorities

by the Mars Exploration
Payload Assessment Group

Chair: Ron Greeley

This document is the result of a series of meetings and workshops (Table 1) collectively involving more than 110 individuals from the Mars community with representatives from universities, research centers and organizations, industry, and international partners for Mars exploration. Although the effort was focused through activities of the *Mars Exploration Payload Analysis Group (MEPAG,* chaired by R. Greeley), participation has been much wider, as indicated in Appendix 2, and builds on the work of the *Mars Expeditions Science Group* led by D. McCleese.

Initial discussions and earlier drafts of this document were centered on Mars Program goals related to *Life, Climate, and Resources,* with the crosscutting theme of "follow the water." It generally has been recognized that geological sciences and investigations that would lead to exploration by humans were incorporated in the "Resources" goal. The consensus reached in August 2000 was that the program **goals** should be recast as *Life, Climate, Geology, and Preparation (for Human Exploration),* with "water" remaining a crosscutting theme.

Table 1. Meetings and workshops used to develop the scientific goals, objectives, investigations, and measurements for Mars exploration.

Group	Date	# of participants
MAST	11–12 Jan. 2000	5
MEPAG/MPRG	22–24 Feb. 2000	101
MAST	6 Jun. 2000	8
MAST	weekly/semi-monthly telecons	3-6
MEPAG	8-10 Aug. 2000	49
MAST	1 Nov. 2000	12
MEPAG	15-17 Nov. 2000	65

MAST (*Mars Ad hoc Science Team)*
MEPAG *(Mars Exploration Payload Analysis group)*
MPRG (*Mars Peer Review Group;* one-time meeting)

The **objectives**, **investigations,** and **measurements** needed for the exploration of Mars have been formulated and prioritized by subgroups of participants focused on the four principal exploration goals. Individuals were free to participate in more than one group during workshops and there were intergroup critiques of the objectives, investigations, and measurements, the results of which are reflected here.

Within each objective, the investigations are listed in priority order as determined within each discipline. There was no attempt to synthesize the overall set of investigations, but it was recognized that synergy among the various goals and objectives could alter the priorities in an overall strategy. Completion of all the investigations will require decades of effort. It is recognized that many investigations will never be truly complete (even if they have a high priority) and that evaluations of missions should be based on how well the investigations are addressed. While priorities should influence the sequence in which the investigations are conducted, it is not intended that they be done serially, as many other factors come into play in the overall Mars Program. An evaluation of the *technology development* needed to conduct each measurement is given as “none,” “some,” or “much.”

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

Objectives A and B are regarded as co-priorities and should be addressed in parallel. Although the investigations and measurements within these objectives are generally ordered by progression from orbital science to surface exploration to sample return, orbital missions should be interleaved synergistically with in situ science and sample return to optimize selection of landing sites and samples for study.

A. Objective: Determine if life exists today.

1. Investigation: **Map the 3-dimensional distribution of water in all its forms.** Zones of liquid water in the subsurface provide the most likely environments for extant life on Mars. In the absence of life, such environments could also sustain prebiotic chemistry of interest for understanding the origin of life on Earth. **Requires global remote sensing of water in all its forms to identify the locations, phases, and, if possible, temporal (seasonal) changes in near-surface water budgets.**

Measurements

a. Global search and mapping of water to 10 km depth at a horizontal spatial resolution of 100 m and a vertical resolution of 10 m for the upper 500 m and a few hundred meters below that depth; must be able to distinguish CO_2 clathrate, ice, and liquid water. *Technology development needed: Modest.*

2. Investigation: **Carry out in situ exploration of areas suspected of harboring liquid water.** Results will be used to validate remote sensing observations and to explore for life or prebiotic chemistry. **Requires subsurface drilling, in situ instrumentation to detect water in all its forms (inclusive of microenvironments; e.g., brine films), CO_2 clathrate, and to analyze rocks, soils, and ices for organic compounds or to detect life.**

Measurements

a. For at least 20 stations at 4 targeted sites (based on remote sensing), conduct in situ geophysical and chemical (e.g., “sniffers”) searches for subsurface water and other volatiles (e.g., carbon dioxide and reduced gases like methane and ammonia) over km^2 surface areas. *Technology development needed: Some.*

Note: The following two investigations (b and c) could be done in parallel.

b. For at least 3 targeted sites, drill initially to 2 m depth and later to 100s of meters and conduct experiments to detect thin films (~50 μm) of water and major and trace volatiles in ices (e.g., carbon dioxide reduced gases such as methane and ammonia) in surface and subsurface soils and atmospheric measurements of trace gases. *Technology development needed: Much (subsurface drilling).*

c. For at least 3 targeted sites, drill initially to 2 m depth and later to 100s of meters and search for biogenic elements (e.g., C, H, N, O, P and S) and their oxidation states, organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.) and chirality. *Technology development needed: Much (subsurface drilling to 10 m and deeper; in situ detection of organics).*

3. Investigation: **Explore high-priority candidate sites (i.e., those that provide access to near-surface liquid water) for evidence of extant (active or dormant) life forms.** Although the means for in situ life detection is poorly defined, basic measurements are likely to include both in situ analysis and laboratory-based analysis of pristine (uncontaminated or unaltered) samples to search for organic and inorganic biosignatures, metabolic activity, isotopic fractionation, disequilibrium chemistry, etc. **Requires in situ life detection experiments on subsurface materials and laboratory analysis of returned core samples**.

Measurements

Note: 3a. could be done in conjunction with 2b and 2c.

a. In situ experiments for at least 3 targeted sites to detect extant or dormant life in soils and ices; could include the search for complex organic compounds at a ppb detection limit (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.), chirality, fluorescent staining and microscopy for specific biomolecules, metabolic products, methods for nucleic acid amplification, and, potentially, culture-based methods to detect growth and metabolism, etc. Methods should include a means for the detection of false positives (i.e., for assessing forward contamination). *Technology development needed: Much.*

b. Sample return (0.5–1.0 kg each from 3 diverse sites) for laboratory-based life detection experiments, such as advanced GC-MS analysis of powdered rocks, microscopy (e.g., light, fluorescent and laser confocal, TEM, SEM, X-ray tomography, laser Raman imaging, etc.) of rock surfaces and interiors to explore for chemical (isotopic, trace elemental, etc.), morphological and mineralogical biosignatures and methods to search for metabolic activity, disequilibrium chemistry, etc. *Technology development needed: Modest for measurement technologies; much for sample containment assurance.*

4. Investigation: **Determine the array of potential energy sources available on Mars to sustain biological processes.** Biological systems require energy that could come from a variety of sources and use a wide variety of transudation mechanisms.

Potential sources include chemical redox, pH gradients, geothermal heat, radioactivity, and incident radiation (sunlight). **Requires orbital mapping, in situ investigations, and sample return.**

Measurements

a. Remote sensing to map biogenic elements (e.g., C, H, N, O, P, and S) and their oxidation states, transition metals, and aqueous minerals [including carbonates, fixed inorganic nitrogen, phosphates, sulfates, halides, metallic oxides (e.g., hematite) and sulfides, clays, etc.]. Need coverage at all high priority sites (5% of planet's surface) that show geomorphic evidence for prolonged hydrological activity. Local coverage of all high-priority sites at a minimum spatial resolution of 100 m (mineral mapping) and a few km (for elemental mapping) at a spectral resolution of 2.5 nm over the range 1.0–5.0 microns. *Technology development needed: Some for halides and metal oxides; Much for elements.*

b. Thermal infrared remote sensing to search for local geothermal "hot-spots" in the shallow crust at a spatial resolution of 100 m. *Technology development needed: None.*

c. Remote sensing to search for point-source concentrations of volatiles (e.g., gas-emitting vents, or "fumeroles") using near and mid-IR spectroscopy at a spatial resolution of a few km. *Technology development needed: Some.*

d. In situ investigations to search for biogenic elements (e.g., C, H, N, O, P, and S) and their oxidation states, transition metals, and aqueous minerals [including carbonates, fixed inorganic nitrogen, phosphates, sulfates, halides, metallic oxides (e.g., hematite) and sulfides, clays, etc.] and evidence of chemical disequilibrium, including gradients and redox chemistry, pH, temperature, radiation, etc. *Technology development needed: Modest.*

e. In situ investigations to explore for specific classes of organic molecules (derivatives of chromophores, including porphyrins and their precursors, pyroles) that are known to be important for energy-transduction in living systems on Earth. *Technology development needed: Modest.*

f. Returned samples (minimum of 0.5–1.0 kg from each of 3 diverse sites) for mineralogical and geochemical characterization (potential analyses include X-ray diffraction, X-ray tomography, X-ray fluorescence, ICP-MS, etc). *Technology development needed: Much.*

<u>5. Investigation:</u> **Determine the nature and inventory of organic carbon in representative soils and ices of the Martian crust.** Carbon is a fundamental building block for life. It may exist within soils and ices in a variety of biotic and abiotic forms. Its distribution would exert a primary control on where and how life could develop. **Requires in situ exploration and sample return.**

Measurements

a. In situ analysis of surface and subsurface (to a few meters depth) soils and ices to search for organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.) and their concentration gradients, and to detect seasonal fluxes in carbon dioxide and reduced gases (e.g., methane, ammonia, etc.). *Technology development needed: Much (in situ organics detection; Much for subsurface drilling).*

b. Returned samples (0.5–1.0 kg from each of 3 diverse sites) to analyze soil and rock cores for organic compounds, including molecular structures, stable isotope compositions (e.g., C, H, N, O, P and S) and their oxidation states. Must also apply methods for assessing sample containment assurance and for detecting false positives (i.e., forward contamination). *Technology development needed: Much.*

6. Investigation: **Determine the distribution of oxidants and their correlation with organics.** Results from Viking suggest that unknown oxidation processes in Martian soils are responsible for the selective destruction of organic compounds. The distribution of oxidants on Mars is likely to have been a controlling factor in determining where, when, and how life might have developed. **Requires instrumentation for determining the elemental chemistry and mineralogy of surface and subsurface samples.**

Measurements

a. In situ experiments at one well-targeted, low-latitude site and 1.0-meter depth to determine gradients in the concentration of electrochemically active species (e.g., oxygen and hydrogen) at ppm concentrations and susceptibility of metallic and organic compounds to oxidation and to determine the spatial and depth distribution of specific classes of oxidizing compounds (e.g., peroxides, etc.). *Technology development needed: Modest.*

B. Objective: Determine if life existed on Mars in the *past*.

1. Investigation: **Determine the locations of sedimentary deposits formed by ancient and recent surface and subsurface hydrological processes.** Such deposits provide the best repositories for preserving a fossil record of ancient Martian life. **Requires global mapping of geomorphology and mineralogy, followed by in situ "ground truth" of mineralogy and geochemistry for remote sensing and to assist the selection of landing sites and samples for return to Earth.**

Measurements

a. Global remote sensing in the visible at 15 m spatial resolution to search for geomorphic features (e.g., paleolake basin shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) indicative of aqueous sedimentary processes. *Technology development needed: None.*

b. Global mapping in the mid-IR (wavelength range: 5–14 μm) at 100 m resolution; targeted at 40 m spatial resolution hyperspectral mapping (1–5 μm, 2.5 nm spectral resolution of aqueous sedimentary deposits (e.g., those targeted at lower resolution based on geomorphic and mineralogical evidence for prolonged aqueous sedimentary processes) to explore for aqueous mineralogies [e.g., carbonates, fixed inorganic nitrogen, phosphate, silica, metallic oxides (e.g., hematite) and sulfides, sulfates, borates, halides, clays, etc.] that are potential repositories for fossil biosignatures. High-spatial-resolution mapping (100 m) in thermal IR to explore for near-surface hydrothermal systems. *Technology development needed: Some.*

c. In situ measurements (e.g., laser Raman, infrared spectroscopy, X-ray diffraction, X-ray fluorescence, etc.) to determine the mineralogy and geochemistry of potential aqueous materials, such as carbonates, fixed inorganic nitrogen, phosphates, silica, sulfates, halides, borates, metallic oxides (e.g., hematite) and sulfides, clays, etc., including hydrous weathering products formed by interactions of primary lithologies with water, conducted at a minimum of 3 diverse sites for obtaining ground truth to calibrate orbital IR measurements. *Technology development needed: Modest.*

2. Investigation: **Search for Martian fossils (morphological and chemical biosignatures of ancient life).** Life can leave a variety of biosignatures in water-deposited rocks. Based on studies of the fossil record on Earth, certain environments and types of deposits provide favorable settings for the preservation of fossil biosignatures. These include environments where fine-grained, clay-rich deposits form in lakes and streams, or where minerals precipitate rapidly from water in the presence of organisms. Locating the most favorable deposits for preserving fossil biosignatures requires remote sensing, in situ analysis, and targeted sample returns.

Measurements

a. Global remote sensing at 15 m spatial resolution in the visible to search for geomorphic features (e.g., paleolake basin and shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) and in the mid- and near-IR to explore for minerals [e.g., carbonates, fixed inorganic nitrogen, phosphates, silica, sulfates, halides, borates, metallic oxides (e.g., hematite) and sulfides, clays, etc.] indicative of aqueous sedimentary processes. *Technology development needed: Some.*

b. In situ analyses of aqueous sedimentary lithologies (e.g., using laser Raman spectroscopy, infrared-spectroscopy, X-ray diffraction/fluorescence, etc.) conducted at a minimum of 3 well-characterized and diverse sites to determine the mineralogies (e.g., aqueous minerals, reduced phases, biominerals, etc.), macro- and micro-scale rock textures and carbon compounds (e.g., total carbon content, the presence of particulate kerogen or more volatile hydrocarbons, etc.) in aqueous sediments (e.g., siliciclastics, carbonates, evaporites, etc.) and to explore for potential biosignatures (e.g., chemofossils, biosedimentary structures, etc.) preserved in sedimentary rocks. *Technology development needed: Some.*

c. Return of targeted samples (0.5–1.0 kg) from each of 3 sites “certified” to be of aqueous sedimentary origin) for detailed microscopic (e.g., light, fluorescence, and laser confocal microscopy; TEM; SEM; X-ray tomography; laser Raman imaging, etc.), geochemical analysis (e.g., isotopic, trace element), mineralogical characterization (e.g., using laser Raman mapping spectroscopy, X-ray diffraction/X-ray fluorescence, etc.), and organic analysis (e.g., gas chromatography-mass spectrometry; laser desorption spectroscopy, etc.) and to search for fossil biosignatures (e.g., organic-walled microfossils or their mineralized replacements, chemofossils (e.g., organic biomarker compounds, isotopic and trace element signatures) and biominerals). *Technology development needed: Much (sample return); Modest (instrumentation).*

3. Investigation: **Determine the timing and duration of hydrologic activity.** To assess the potential for the origin and evolution of life on Mars during the planet’s history, knowledge is needed for when, where, and how long liquid water environments were present at the surface and in the subsurface. This requires the development of stratigraphic (age) frameworks for deposits based on remote sensing, in situ measurements, and samples returned from key sites for radiometric.

Measurements

a. In situ (using mobile platforms and subsurface drills) exploration for aqueous minerals [e.g., carbonates, fixed inorganic nitrogen, phosphates, silica, metallic oxides (e.g., hematite) and sulfides, sulfates, borates, halides, clays, etc.], water-formed geomorphic features (e.g., paleolake basin and shoreline deposits, fluvial-deltaic deposits, hydrothermal spring mounds, etc.) and diagnostic meso-scale sedimentary structures (e.g., planar cross bedding, oscillation ripples, mudcracks, teepee structures, various biogenic sedimentary structures, etc.) indicative of hydrologic activity. These detailed investigations should be conducted for at least 6 diverse units. *Technology development needed: Modest (rover development); None (instrumentation); Much (preparing for human exploration).*

b. Returned samples from at least 6 units suitable for establishing valid radiometric dates to calibrate the geologic timescale for Mars. Integrated petrographic and geochemical analyses for understanding initial isotopic ratios and the effects of shock metamorphism and weathering processes on the reliability of age dates. Note: Sampling strategies could include sites where diverse lithologies and units could be sampled at a single site. If overlapped with human exploration, initial sample analysis might be done at Mars. *Technology development needed: Modest (rover development); None (instrumentation); Much (preparing for human exploration).*

C. Objective: Assess the extent of *prebiotic organic chemical evolution*.

1. Investigation: **Search for complex organic molecules in rocks and soils.** The steps in prebiotic chemistry that lead to life on Earth are unknown. On Earth, the record of those early events has been largely destroyed by plate tectonics and weathering. If life arose on Mars, it probably would have consumed and transformed much of the original organic inventory present. However, if life did not arise, the record of prebiotic chemistry that developed in an Earth-like setting on early Mars is considered fundamentally important for developing the understanding of the chemical steps that preceded the appearance of life on Earth. Because Mars apparently lacks plate tectonics, it might provide an unrivaled record of early prebiotic chemical events in an Earth-like setting. The exploration for prebiotic chemistry ultimately requires a different approach than the search for the extant biochemistry. The search for prebiotic chemistry requires studies of modern aqueous environments (e.g., groundwater, ice-brine transitions, hydrothermal systems, etc.) and the record of aqueous paleoenvironments preserved in ancient sedimentary rocks. Targets for in situ studies must be first identified by remote sensing based on geomorphology and mineralogy (see I.A.1) and then mobile platforms (rovers) used to determine mineralogy, geochemistry, organic chemistry, and returned samples.

Measurements

a. In situ/mobile platforms deployed to at least 3 well-characterized and diverse sites to assess the mineralogy (e.g., using laser Raman mapping spectroscopy, X-ray diffraction/X-ray fluorescence, etc.), geochemistry (e.g., alpha proton or mass spectrometer methods for elemental and isotopic compositions) and organic materials (e.g., gas chromatography-mass spectrometry; laser desorption spectroscopy, etc.). *Technology development needed: Modest (rover development); Some (in situ instrumentation).*

b. Return samples from at least 6 units suitable for radiometric dating to calibrate the geologic timescale of Mars. Integrated petrographic and geochemical analyses for understanding initial isotopic ratios and the effects of shock metamorphism and weathering on age date reliability. Measurement of other volatile components (e.g., D/H) to calibrate volatile history. *Technology development needed: Much (sample return); Some (lab instrumentation).*

<u>2. Investigation:</u> **Determine the changes in crustal and atmospheric inventories of carbon through time.** Changes in the atmospheric and crustal carbon inventories over geologic time would have greatly affected the prebiotic chemistry and climate of the Martian surface and, hence, the potential for life to develop. The detailed history of the carbon cycle will require intensive sample analysis of a wide range of rock types and ages. This objective parallels investigation I.A.5. (determine the crustal inventory of carbon) but seeks to integrate that information over time. Thus, the objective is posed in a historical way that will require a stratigraphic (temporal) framework for sampling (established through detailed geological mapping from orbit), in situ drilling and samples returned to Earth for detailed chemical analysis of carbon compounds, and radiometric dating of samples.

Measurements

a. Global remote sensing in the near-infrared at ~40 m spatial resolution to map mineralogy. *Technology development needed: Modest.*

b. Returned samples (0.5–1.0 kg) from at least 6 well-dated, temporally diverse sites for both organic and inorganic carbon analysis [e.g., ratios of carbon isotopes, simple inorganic (e.g., bound volatiles like CO, CO_2, CH_4, etc.) and analysis of complex organic compounds (e.g., amino acids, proteins, carbohydrates, lipids, nucleic acids, etc.)] preserved in rocks, soils, and ices. *Technology development needed: Much.*

c. Returned samples from at least 6 temporally diverse units to establish radiometric dates to calibrate the geologic timescale. *Technology development needed: Much. [Note: In this context, technology (instrumentation) developments for precise in situ dating on Mars could mitigate the need for returned samples.]*

II. GOAL: DETERMINE CLIMATE ON MARS

A. Objective: Characterize Mars' present climate and climate processes (investigations in priority order)

***1. Investigation:* Determine the processes controlling the present distributions of water, carbon dioxide, and dust.** Understanding the factors that control the annual variations of volatiles and dust is necessary to determine to what extent today's processes have controlled climate change in the past. **Requires global mapping and then landed observations on daily and seasonal timescales.**

Measurements (a, b, and c concurrently)

a. Global mapping with sufficient temporal resolution **(*define*)** to characterize seasonal variations of dust, water vapor, carbon dioxide, and temperature requires *daily* global coverage of the planet with *horizontal resolutions* equal to, or better than, 5 degrees latitude and 30 degrees longitude. Some sampling of *diurnal* variations (e.g., day-night contrasts) is required to understand aliasing of longer-term measurements. Water vapor, dust extinction, and meteorological measurements taken *concurrently* (within one hour of one another). Vertical measurements are required with *half-scale height* resolution (< 5 km) over the following height ranges:

- Water vapor: 0–40 km with sensitivities of 3–30% in mixing ratios over that range for reasonable water amounts (e.g., 5–10 precipitable microns column amounts)
- Dust and water ice cloud extinction: 0–60 km with ± 10% in extinction
- Temperature/pressure: 0–80 km with typically 1–2 K precision and pressure registration to ± 1%

- Surface pressure: Required precision is a few percent for seasonal variations, < 1 % relative precision for dynamical (weather) variations
- Energy balance: Albedo and thermal irradiance measurements adequate to compute surface net heat balance (and equivalent carbon dioxide flux) to ± 20% over representative regions of the permanent and seasonal polar caps.

Technology development needed: Modest.

b. Estimate water vapor flux, requiring in situ daily, diurnally resolved measurements of near-surface water vapor concentration over (latitudinally dependent) seasonal timescales (e.g., 60 sols in polar regions; 1 Mars year at nonpolar latitudes). Measurements needed at low, mid, and high latitudes and in a variety of terrain (not necessarily concurrently): low and high thermal inertia regions, off and on the residual north polar cap. Measurements from a site with subliming seasonal frost also desired. *Technology development needed: Some.*

c. In situ measurements of adsorbed and solid water and carbon dioxide in the soil concurrent with the measurements described in (a) and (b) above to depths of a few cm at multiple times per day. Ice abundance measurements should cover the range from 0.01 to 1.0 g cm^3 with 10% accuracy. Adsorbed H_2O measurements should cover the range from 10^{-4} g/g to 10^{-2} g/g with 10% accuracy. Measurements of adsorbed CO_2 should cover the range from 10^{-5}g/g to 10^{-3}g/g with 20% accuracy. Measurements adsorbed H_2O and CO_2 and water ice should also be conducted to depths of ~1 meter, but do not require diurnal or even seasonal temporal resolution. *Technology development needed: Some.*

d. Detect near-surface (< 100 m) and deep (100 m–5 km) liquid water; global mapping at scales of 10° longitude by 30° latitude. Determine depths to ± 10 m for near-surface water, ± 100 m at greater depth. *Technology development needed: Much.*

e. Detect subsurface ice with precisions of 100–200 m as deep as 5 km, at horizontal scales of a few hundred kilometers. *Technology development needed: Much.*

f. In situ meteorological measurements:

- *Seasonal monitoring*: Hourly measurements of temperature, pressure, and atmospheric column dust opacity from 16 or more globally distributed sites for one Mars year.
- *Weather monitoring*: Diurnally resolved (e.g., hourly) measurements of pressure, wind speed and direction, temperature, and optical depths from sites at high, middle, and low latitudes, in both hemispheres, for a Mars year or longer. (At polar sites, winter measurements are not required, but are desirable.)
- *Boundary layer processes*: High-frequency measurements (comparable to, or better than, 1 sec sampling) of near-surface wind, temperature, and water vapor concentration for representative portions (~ 15 minute sampling

intervals) of diurnal cycle (e.g., pre-dawn, mid-morning, mid-afternoon and post-sunset). Needed for representative sites at low, mid, and high latitudes; low and high thermal inertia nonpolar sites; one site dominated by local topography (e.g., canyon or edge of layered terrain). Vertical temperature profiling (1–3 levels minimum) highly desired through first few meters.

Technology development needed: Some.

g. Returned samples to study the physical, chemical, and geological properties of rocks and soils and their interaction with the atmosphere and hydrosphere. Samples taken from 1 m depth soil and of rock weathering rinds; samples needed from one representative low-latitude site (0 to 30°), and one high-latitude site (60–90°). *Technology development needed: Much.*

2. *Investigation:* ***Determine the present-day stable isotopic and noble gas composition of the present-day bulk atmosphere.*** These provide quantitative constraints on the evolution of atmospheric composition and on the source and sinks of the major gas inventories.

Measurements

a. In situ, high-precision measurements of atmospheric isotopic composition at one site. ± 5 per mil for 18-O/16-O, 17-O/16-O, 13-C/12-C; ± 250 per mil for D/H, anywhere on the planet. *Technology development needed: Much.*

b. Sample return of pristine atmospheric samples for measurement of key elements such as 40-Ar and 129-Xe. *Technology development needed: Much.*

3. *Investigation:* ***Determine long-term trends in the present climate.*** This determination will test to what degree the Martian climate is changing today.

Measurements

a. Extension of the orbital and lander measurements of (A1) to multiple Mars years. *Technology development needed: Much.*

b. Long-term (at least 10 years), in situ monitoring of key atmospheric variables (e.g., pressure, temperature, dust opacity, water) at globally representative sites (network science) for at least 12 sites. *Technology development needed: Much.*

4. *Investigation:* ***Determine the rates of escape of key species from the Martian atmosphere, and their correlation with solar variability and lower atmosphere phenomenon (e.g., dust storms).*** **Requires global orbiter observations of species (particularly H, O, CO, CO_2, and key isotopes) in the upper atmosphere, and monitoring their variability over multiple Martian years.**

Measurements

a. Map from orbit the 3-D distribution of key atmospheric neutral and charged species such as H, O, CO, CO_2, and key isotopes. *Technology development needed: None.*

b. Measure from orbit the variations of key atmospheric neutral and charged species (H, O, CO, CO_2, and key isotopes) over seasonal cycles, through dust storm events, and over the solar cycle. *Technology development needed: None.*

5. *Investigation:* *Search for micro-climates.* Detection of exceptionally or recently wet or warm locales and areas of significant change in surface accumulations of volatiles or dust would identify sites for in situ exploration. Requires global search for sites based on topography or changes in volatile distributions and surface properties (e.g., temperature or albedo).

Measurements

a. Detect hot spots (e.g., surface geothermal activity) at spatial resolution of <100 m. *Technology development needed: Some.*

b. Detect local concentrations of water vapor, particularly within the lowest 1–3 km the atmosphere at spatial resolution <100 m. Regions repeatedly surveyed during spring and summer seasons. *Technology development needed: Some.*

6. *Investigation:* *Determine the production and reaction rates of key photochemical species (O_3, H_2O_2, CO, OH, etc.) and their interaction with surface materials.*

Measurements

a. Measure species in the atmosphere with sensitivities of 10^9 cm=3 as a function of insolation. *Technology development needed: Some.*

b. Measure and identify surface complexes or chemabsorbed species on a representative sample **(sample return or in situ ?)** of surface materials (primary and secondary materials). *Technology development needed: Much.*

B. Objective: Characterize Mars' ancient climate and climate processes (investigations in priority order)

1. *Investigation:* *Find physical and chemical records of past climates.* These provide the basis for understanding the extent and timing (e.g., gradual change or abrupt transition) of past climates on Mars. **Requires: remote sensing of stratigraphy and aqueous weathering products, landed exploration, and returned samples.**

Measurements

a. Remote sensing of 100s of target sites in the visible at 15 cm/pixel or better to characterize fine-scale layers in sedimentary deposits. The interpretation of high-resolution data requires lower-resolution context images. *Technology development needed: Some.*

b. Hyperspectral orbital remote sensing at resolutions of 20–50 m/pixel to search for and characterize aqueous alteration and deposition products such as carbonates, hydrates, and evaporites. *Technology development needed: Some.*

c. In situ exploration of layered deposits to characterize the physical structure of layers the chemistry, trace elements, isotopic (especially H, N, and O), mineralogy, and petrology for two regions (polar and nonpolar) on the planet, at multiple stratigraphic locations at each site. *Technology development needed: Much.*

d. Returned samples of soils, rocks, atmosphere, and trapped gasses/ices to measure the chemistry, mineralogy, and ages. A single sample is a major advance, but multiple samples spanning a range of ages is highly desirable. *Technology development needed: Much.*

2. *Investigation:* ***Characterize history of stratigraphic records of climate change at the polar layered deposits, the residual ice caps.*** The polar regions suggest repeated geologically recent climate change. A key to understanding their histories is relative dating of polar layering and volatile reservoirs. **Requires orbital, in situ observations and returned samples.**

Measurements

a. Orbital or aerial platform remote sensing of 100s of sites in the visible at 15 cm/pixel or better to characterize fine-scale layers in both north and south polar layered deposits. *Technology development needed: Some.*

b. Hyperspectral orbital remote sensing at resolutions of 20–50 m/pixel to search for and characterize physical properties, composition and morphology, volatile composition of north and south polar deposits. If NIR spectra are used, the coverage should extend to 4 microns. *Technology development needed: Some.*

c. In situ, local exploration of layered deposits in north and south polar regions to characterize the physical structure of layers, volatile content, chemical and isotopic (especially H, N, and O) variations. Measurements should be conducted at multiple stratigraphic locations at each site. *Technology development needed: Much.*

d. Returned samples of polar layered deposits that preserve fine-scale stratigraphy, ices, and trapped gasses, and enable measurements of chemistry, mineralogy, and determination of ages. Multiple samples spanning a range of ages are desirable to search for episodic volcanic activity, major impact events, or large-scale environmental variability due to changes in Mars' orbital and axial elements. *Technology development needed: Much.*

III. GOAL: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS ("Geology")

A. Objective: Determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration etc.) that have created and modified the Martian crust and surface (investigations in priority order)

1. Investigation:* *Determine the present state, distribution, and cycling of water on Mars. Water is arguably the most important geologic material that influences most geological processes, including the formation of sedimentary, igneous and metamorphic rocks, the weathering of geological materials, and deformation of the lithosphere. **Requires global observations using geophysical sounding and neutron spectroscopy, coupled with measurements from landers, rovers, and the subsurface.**

Measurements

a. Global search for water to a depth of several kilometers at spatial scales of ~ 100 m and to a depth resolution of 100 m. *Technology development needed: Some.*

b. Aerial platform remote sensing to search for subsurface water to a depth of 500 m at a depth resolution of 10 m and a spatial resolution of 100 m. *Technology development needed: Some.*

c. Acquire vertical profiles of the distribution of subsurface liquid water and ice at several sites where water is likely from the sounding measurements in (a) and (b). *Technology development needed: Much.*

d. In situ drilling to liquid water or ice to depths up to a kilometer for at least one site and to depths of several hundred meters for several sites with down-hole instruments to determine elemental abundances, mineralogy of volatile and other phases, including ices. *Technology development needed: Much.*

e. Identify and measure the abundance of water-bearing minerals for several diverse sites of different ages. *Technology development needed: Much.*

2. Investigation:* *Evaluate sedimentary processes and their evolution through time, up to and including the present. Fluvial and lacustrine sediments are likely sites to detect traces of prebiotic compounds and evidence of life. Sediments also record the history of water processes on Mars. Eolian sediments record a combination of globally averaged and locally derived fine-grained sediments and weathering products. Sediments are also likely past or present aquifers. **Requires knowledge of the age, sequence, lithology, and composition of sedimentary rocks (including chemical deposits), as well as the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport processes.**

Measurements

a. Global stereo imaging with at least 10 m/pixel resolution and contiguous regional coverage of at least 1 percent of the planet at better than 1 m/pixel. *Technology development needed: None.*

b. Global orbital remote sensing with access to the entire planet at 30 m/pixel in the visible to reflected infrared (0.4 to 5 micrometers) with a spectral resolution of 10 cm^{-1}. *Technology development needed: Some.*

c. In situ measurements, including traverses across sedimentary units of different ages for several sites to determine physical properties of rocks and fines and their chemistry, mineralogy, lithology, and petrology. Characterization should be sufficient to identify the rock types, their mode of deposition and degree of alteration. *Technology development needed: Some.*

d. Returned samples for detailed characterization from at least several sites containing water-lain sediments, for which *valid* surface ages can be obtained in order to constrain the sedimentary record. *Technology development needed: Much.*

e. Drilling to 1 km at one site and to ~100 m at several sites to determine the physical properties of rocks and fines and their chemistry, mineralogy, and petrology. *Technology development needed: Much.*

3. *Investigation:* ***Calibrate the cratering record and absolute ages for Mars.*** The evolution of the surface, interior, and surface of Mars, as well as possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. **Requires absolute ages on returned rock (not soil) samples of known crater ages.**

Measurements

a. Returned samples of volcanic rocks whose cratering age dates the same event as its radiometric age from at least two key sites, chosen to resolve uncertainties in crater ages (one focusing on early to mid Mars history and one relatively young). *Technology development needed: Much.*

b. Measurement of current impact flux from seismic network and an infrasonic network operating for 1 Mars year, using 12 stations arrayed in triangular groups of 3 spaced 100–200 km apart. *Technology development needed: Much.*

c. Measurement of the current impact flux from by orbital detection of ionospheric perturbations induced by meteorite entry. *Technology development needed: Much.*

4. *<u>Investigation:</u>* *Evaluate igneous processes and their evolution through time, including the present*. This study includes volcanic outgassing and volatile evolution. Volcanic processes are the primary mechanism for release of water and atmospheric gasses that support potential past and present life and human exploration. Sites of present day volcanism, if any, may be prime sites for the search for life. **Requires global imaging, geologic mapping, techniques for distinguishing igneous and sedimentary rocks, evaluation of current activity from seismic monitoring, and returned samples.**

Measurements

a. Orbital remote sensing, including stereo, in the visible (better than 1 m/pixel with ~10 m/pixel context images as listed above in III.A.2.a) and hyperspectral data of 30 m/pixel spatial resolution for key igneous regions of Mars (~20 % of surface). *Technology development needed: Some.*

b. In situ measurements from the surface for at least several volcanic sites to determine chemistry, mineralogy, and petrology. Characterization should be sufficient to identify the rock types and will require a payload with significantly more capability than Athena. *Technology development needed: Some.*

c. Global seismic monitoring of potential volcanic activity using an array of broad-band (0.05 to 50 Hz) seismometers (12 stations in groups of three with an internal spacing of 100–200 km) distributed globally. *Technology development needed: Some.*

d. Returned samples of a variety of igneous rocks from at least two sites of different ages and types for geochemical, isotopic, mineralogical, and petrographic analysis to understand the chemistry and physical process in the magma source regions and how they have changed with time. *Technology development needed: Much.*

e. Search for thermal anomalies at a horizontal resolution of tens of meters. *Technology development needed: Some.*

5. *<u>Investigation:</u>* *Characterize surface-atmosphere interactions on Mars, including polar, eolian, chemical, weathering, and mass-wasting processes.* Interest here is in processes that have operated for the last million years as recorded in the upper 1 m to 1 km of geological materials. Understanding present geologic, hydrologic, and atmospheric processes is the key to understanding past environments and possible locations for near-surface water. Knowing the chemistry and mineralogy of both near-surface rocks and alteration products is essential for calibrating remote sensing data. This study also has strong implications for resources and hazards for future human exploration. **Requires orbital remote sensing of surface and subsurface,**

and in situ measurements of sediments and atmospheric boundary layer processes.

Measurements

a. Orbital remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel) for key terrains (a total of ~ 20 % of the surface). *Technology development needed: None.*

b. Global SAR mapping of subsurface structures (below surficial materials) at depths up to several meters at spatial resolutions of 100 m/pixel. *Technology development needed: Some.*

c. In situ analysis of sediment grain size distribution, textures, composition, and mineralogy of the regolith and characterization of the weathering rind on rocks at several sites. *Technology development needed: Some.*

d. Network of at least 16 stations to monitor weather (temperature, pressure, wind velocity, and strength) with concurrent visual observations from the surface and from orbit. Mission lifetime of 3 Mars years to determine seasonal and internal variations. *Technology development needed: None.*

e. A diverse set of returned samples, including soil profiles, duricrust and rock, from several sites (for detailed mineralogy of weathered products, isotopic fractionation, nature of weathering rinds, if any, and so on). *Technology development needed: Much.*

6. *Investigation:* ***Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations. This includes, for example, the structure and origin of hemispheric dichotomy.*** The vertical and global variation of rock properties and composition record formative events in the planet's early history place constraints on the distribution of subsurface aquifers, and aid interpretation of past igneous and sedimentary processes. **Requires remote sensing and geophysical sounding from orbiters and surface systems, geologic mapping, in situ analysis of mineralogy and composition of surface material, returned samples, and seismic monitoring.**

Measurements

a. Global remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel). *Technology development needed: None.*

b. SAR mapping of subsurface structure to depths up to several meters and at 100 m spatial resolution. *Technology development needed: Some.*

c. In situ measurements of physical properties of rocks and fines for chemistry, mineralogy, petrology at several sites of diverse ages and types. *Technology development needed: None.*

d. Long-term (at least 1 Mars year) global seismic measurements using an array of broad-band (0.01 to 20 Hz) seismometers (at least 12 stations distributed in groups of at least 3, with internal spacing of 100–200 km). *Technology development needed: None.*

e. Returned samples of igneous rocks from several diverse units of different ages for detailed physical, chemical, and geologic analyses. *Technology development needed: Much.*

f. Global gravity survey to precision of 10 mgal spatial (wavelength) resolution of 175 km. This will require precision tracking at low (~200 km) altitude and application of drag compensation techniques. *Technology development needed: Some.*

g. Drilling to 1 km at one site and to ~100 m at several sites to determine the physical properties of rocks and fines and their chemistry, mineralogy, and petrology. *Technology development needed: Much.*

h. Active seismic reflection and refraction measurements to delineate the third dimension, density, and physical properties of the crust and geological units. *Technology development needed: Some.*

i. Regional gravity surveys to precision of <1 mgal over spatial scales of tens of meters for understanding the local third dimensional geometry of the crust and geological units. *Technology development needed: Some.*

7. *Investigation:* *Document the tectonic history of the Martian crust, including present activity.* Understanding of the temporal evolution of internal processes places constraints on release of volatiles from differentiation and volcanic activity and the effect of tectonic structures (faults and fractures in particular) on subsurface hydrology. **Requires geologic mapping using global topographic data combined with high-resolution images, magnetic and gravity data, and seismic monitoring.**

Measurements

a. Global remote sensing, including stereo, in the visible (better than 1 m/pixel with 10 m/pixel context), and hyperspectral (30 m/pixel). *Technology development needed: None.*

b. Global magnetic measurements (spacing better than 50 km) to an accuracy of better than 0.5 nT at an altitude no greater than 100–120 km. *Technology development needed: Some.*

c. Regional magnetic surveys in regions with substantial anomalies using aerial platforms at altitudes of 1–5 km. *Technology development needed: Much.*

d. Global gravity survey to precision of 10 mgal spatial (wavelength) resolution of 175 km. This will require precision tracking at low (~200 km) altitude and application of drag compensation techniques. *Technology development needed: Some.*

e. Regional gravity surveys to precision of <1 mgal over spatial scales of tens of meters for understanding the geometry of structural features with depth. *Technology development needed: Some.*

f. Active seismic reflection and refraction measurements to delineate the geometry (with depth) of structures and tectonic features and regions. *Technology development needed: Some.*

g. Measure crustal in situ stress and strain in drill holes using well pressurization, bore hole break outs, and down hole, well logging measurement techniques. *Technology development needed: Much.*

8. Investigation: ***Evaluate the distribution and intensity of impact and volcanic hydrothermal processes through time, up to and including the present.*** Hydrothermal systems are thought to be the connected with the earliest evolution of life on the Earth. Hydrothermal systems also play an important role in the chemical and isotopic evolution of the atmosphere, and the formation of the Martian soil. Deposits from hydrothermal systems have the potential to record the history of the biosphere and crust-atmosphere interactions throughout Martian history. **Requires knowledge of the age and duration of the hydrothermal system, the heat source, and the isotopic and trace element chemistry and mineralogy of the materials deposited.**

Measurements

a. Global and detailed imaging to search for and characterize candidate volcanic and impact crater locations, including volcanoes with channels systems, and impact crater walls and central uplifts. *Technology development needed: None.*

b. In situ measurements, including traverses across hydrothermal systems present at the surface or exposed by impacts, or other erosional processes with capabilities similar to those listed under III.A.2.c. *Technology development needed: Some.*

c. Returned samples covering the range of available lithologies from at least several sites ranging from very recent to very old. *Technology development needed: Much.*

B. Objective: Characterize the structure, composition, dynamics, and history of Mars' interior (investigations in priority order)

1. *Investigation:* ***Characterize the configuration of Mars' interior.*** This is needed to understand the origin and thermal evolution of Mars and the relationships to surface evolution and release of water and atmospheric gasses. **Requires orbital and lander data.**

Measurements

a. Global gravity survey to 10 mgal precision and 175 km spatial resolution. *Technology development needed: Some.*

b. Global magnetic measurements spaced <50 km to an accuracy of 0.5 nT or better at an altitude <100-120 km. *Technology development needed: Some.*

c. Concurrent measurement of rotational dynamics from at least two landers to a precision better than 10 cm. *Technology development needed: None.*

d. Global seismic monitoring using an array of very broad-band (DC to 10 Hz) seismometers (at least 12 stations in groups of 3 with internal spacing of 100–200 km) operating for 1 Mars year. *Technology development needed: Some.*

e. Returned samples of a variety of fresh volcanic rocks from several diverse sites, including those where rocks excavated from deep within the crust by large impacts are available for sampling. *Technology development needed: Much.*

2. *Investigation:* ***Determine the history of the magnetic field.*** Evidence that Mars had a magnetic field early in its history has important implications for the retention of its early atmosphere and for the shielding of the surface from incoming radiation and the possible evolution of life. **Requires orbiter in eccentric orbit or low-altitude platform.**

Measurements

a. Global magnetic measurements (spacing < 50 km) to an accuracy of better than 0.5 nT from an altitude <100–120 km. *Technology development needed: Some.*

b. Regional magnetic surveys in areas with a large remanent signature using aerial platforms at altitudes of 1–5 km. *Technology development needed: Some.*

c. Samples of a variety of volcanic rocks of different ages from different sites, the sampling being performed such that knowledge of the orientation of the samples is preserved. *Technology development needed: Much.*

d. Long-term (at least 1 Mars year) global seismic measurements using an array of broad-band (0.01 to 20 Hz) seismometers (at least 12 stations distributed in groups of at least 3, with internal spacing of 100–200 km). *Technology development needed: Much.*

3. *Investigation:* *Determine the chemical and thermal evolution of the planet.* Knowledge of the thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gasses) to the surface. **Requires measurements from orbiter and lander.**

Measurements

a. Global gravity survey to 10 mgal precision and 175 km spatial resolution. *Technology development needed: Some.*

b. Global magnetic measurements spaced <50 km to an accuracy of 0.5 nT or better at an altitude <100–120 km. *Technology development needed: Some.*

c. Concurrent measurement of rotational dynamics from at least two landers to a precision better than 10 cm. *Technology development needed: None.*

d. Global seismic monitoring using an array of very broad-band (DC to 10 Hz) seismometers (at least 12 stations in groups of 3 with internal spacing of 100–200 km) operating for 1 Mars year. *Technology development needed: Some.*

e. In situ heat flow measurements to a precision of 5 mW/m^2 for at least 3 sites representing highland crust, lowlands, and recent volcanism. *Technology development needed: Much.*

f. Returned samples of a diverse array of igneous rocks of different ages. *Technology development needed: Much.*

GOAL IV: PREPARE FOR HUMAN EXPLORATION

A. Objective: Acquire Martian environmental data sets (priority order of investigations under review)

1. Investigation: Determine the radiation environment at the Martian surface and the shielding properties of the Martian atmosphere. The propagation of high-energy particles through the Martian atmosphere must be understood, and the measurement of secondary particles must be made at the surface to determine the buffering (or amplifying) effects of the Martian atmosphere, and the backscatter effects of the regolith. **Requires simultaneous monitoring of the radiation in Mars' orbit and at the surface, including the ability to determine the directionality of the neutrons at the surface.**

Measurements

a. Measure charged particle spectra, at the surface and in orbit, accumulated absorbed dose and dose rate in tissue as a function of time over time, particularly at solar maximum and solar minimum. *Technology development needed: Some.*

b. Determine the radiation quality factor, determine the energy deposition spectrum from 0.1 keV/µm to 1500 keV/µm, and separate the contributions of protons, neutrons, and HZE particles to these quantities. *Technology development needed: None.*

c. Measure neutron energy spectrum from 100 keV to 50 MeV or above. The ability to obtain information on the source of the neutrons (depth in soil, atmosphere) is a strongly desirable feature and therefore provisions for assessing direction of incidence of the neutrons are required. *Technology development needed: Some.*

d. Simultaneous surface and orbital measurements are required to determine the shielding component of the atmosphere. *Technology development needed: Some.*

e. Simultaneously measure the atmospheric pressure at the surface of Mars and the atmospheric dust loading. *Technology development needed: Some.*

f. Measure the natural radioactivity of the planet's surface materials (soil and rocks). *Technology development needed: None.*

***2. Investigation:* Characterize the chemical and biological properties of the soil and dust.** Toxicity and reactivity needed to develop hazard mitigation strategies to ensure safety of human explorers on the Martian surface. Requires in situ experiments. If in situ experiments cannot achieve adequate levels of risk characterization, returned samples will be required. The requirements can and may have to be met through sample studies on Earth. Earth sample return provides significant benefits to HEDS technology development programs.

Measurements

a. In situ determination of the toxic trace elements and mineral species including, but not limited to, As, Be, Cd, Cl, F, and Pb. *Technology development needed: Some.*

b. Determine the toxic and genotoxic potential of dust and soil to biological cell analogs (enzymes, lipids, nucleic acids, etc.), to identify reactivity of quasi-cellular systems from which the potential for acute toxicity for human explorers could be inferred. *Technology development needed: Some.*

c. Determine the chemical reactivities with a sensitivity of ppm (of particular interest are changes in the reactivities upon heating, with exposure to humidity, and with emphasis on the identification and volatility of the gases evolved) and up to a maximum depth of 150 cm. Understand the solubility in water of Martian soil (total weight loss after water is equilibrated with the soil), the before and after composition of the soil, and the composition of the aqueous phase in equilibrium with Martian soil. *Technology development needed: Much.*

d. Determine the depth of the superoxidation zone at several locations. *Technology development needed: Much.*

e. In situ sensors or analytical tools to determine the content of carbon and complex organic compounds in wind-blown dust, surface soil, and materials from secluded environments to a sensitivity of 10 ppm. *Technology development needed: Much.*

f. Biohazard assessment. *Technology development needed: Much.*

g. Determine physical properties (size, shape, hardness, adhesion) of representative dust samples: *Technology development needed: Some.*

3. Investigation: ***Understand the distribution of accessible water in soils, regolith, and Martian groundwater systems.*** Water is a principal resource to humans. **Requires geophysical investigations, subsurface drilling, and in situ sample analysis.**

Measurements

a. Map the Martian subsurface for ice and liquid water reservoirs. *Technology development needed: Much.*

b. Measure the vertical distribution (and ultimately comprehensive 3-dimensional subsurface maps) of permafrost, water ice and liquid water with a vertical resolution of ~ 10 m at selected sites. *Technology development needed: Much.*

c. Determine the adsorbed and bound water content of soil samples from several provenances (air-borne dust, surface fines, sand dunes) with precision of ± 10% down to levels of 0.1%. Determine the release temperature of water over the range 0ºC–600ºC. *Technology development needed: Much.*

4. Investigation: ***Measure atmospheric parameters and variations that affect atmospheric flight.*** Pressure and density versus altitude, temporal and spatial variations. **Requires instrumented aeroentry shells or aerostats.**

Measurements

a. Measure and record pressure versus altitude, and temperature for all Mars entry vehicles during the E/D/L phase of the mission. *Technology development needed: Some.*

b. Measure basic surface meteorology: temperature, pressure, wind speed and direction at different sites. *Technology development needed: Some.*

c. Monitor global weather patterns from orbit. *Technology development needed: None.*

d. Measure the frequency and magnitude of dust storms at selected surface locations; characterize the processes active in these storms in terms of the associated wind speeds, pressure changes, atmospheric dust loading. *Technology development needed: None.*

e. Detect local atmospheric vorticity in terms of frequency of local “dust devil” development, quantity of dust lofted, associated wind speeds, and pressure differentials. *Technology development needed: None.*

5. Investigation: ***Determine electrical effects in the atmosphere***. Needed to understand the role of electrical discharge, electrostatic effects, etc., in atmospheric processes, including dust-raising and potential hazards to surface operations**. Requires experiments on a lander.**

Measurements

a. Measure the electrical properties of dust in the atmosphere and observe the consequences of dust electrification. *Technology development needed: Much.*

b. Determine the atmospheric electrification due to turbulent motion in dust clouds and dust storms; determine the population of atmospheric ions and whether there is a diurnal variation; determine what types of discharges occur on Mars. *Technology development needed: Much.*

c. Determine the electrostatic charge state (magnitude, sign, and longevity of charges) for both aerosols and soil particles up to 100 microns. *Technology development needed: Much.*

d. Determine Paschen curves (electrical breakdown in gases) for Mars as a function of temperature, pressure, wind, dust load in atmosphere, and season for meteorological use and as a tool for designing and safeguarding equipment for Mars exploration. *Technology development needed: Some.*

6. Investigation: ***Measure the engineering properties of the Martian surface.*** Soil and surface engineering data (bearing strength, angle of repose, geoelectric properties, etc.) **Requires in situ measurements at selected sites.**

Measurements

a. Measure soil bearing strength and surface penetration resistance. *Technology development needed: None.*

b. Measure soil cohesion and angle of repose. *Technology development needed: None.*

c. Measure soil magnetic and electrostatic properties (adhesion potential, strength of adhesion, and character of the charge). *Technology development needed: Some.*

d. Measure surface temperature and touch temperature of surface features. *Technology development needed: None.*

e. Measure surface heat capacity. *Technology development needed: None.*

f. Measure surface albedo. *Technology development needed: None.*

g. Measure surface thermal conductivity/insulation properties. *Technology development needed: Some.*

h. Determine the particle size and distribution, in the range 0.01 to 10.0 microns (0.01 to about 10 cm surface depth), with higher emphasis on particles much smaller than 1.0 micron. *Technology development needed: Some.*

i. Determine the total columnar suspended load of dust in the atmosphere. *Technology development needed: Some.*

j. Measure average surface sink temperature. *Technology development needed: Some.*

k. Determine soil and dust chemical composition. *Technology development needed: Some.*

l. Measure the conductivity, resistivity, dielectric constant, and piezoelectric properties of the subsurface to a depth of 10 m as a function of latitude, time of year, and geological environment. *Technology development needed: Some.*

m. Measure subsurface distribution of ground ice. *Technology development needed: Some.*

***<u>7. Investigation:</u>* Determine the radiation shielding properties of the Martian regolith.** Soil and dust from the Martian surface offer a readily available source of shielding material for surface crews. The thickness of the required regolith cover will depend upon the measured shielding properties. **Requires an understanding of the regolith composition, a lander with the ability to bury sensors at various depths up to a few meters. Some of the in situ measured properties may be verified with a returned sample.**

Measurements

Determine the radiation shielding characteristics of Martian regolith as a function of cover depth. Radiation sensors would be placed under various depth of regolith cover, and their readings correlated with an unburied sensor. *Technology development needed: Much.*

<u>8. Investigation:</u> Measure the ability of Martian soil to support plant life. Determine the ability of the indigenous soil to support life, such as plant growth, for future human missions. **Requires in situ measurements and process verification.**

Measurements

Conduct in situ process verification of plant growth experiment through full plant growth, seed and re-germination cycle. *Technology development needed: Much.*

<u>9. Investigation:</u> Characterize the topography, engineering properties, and other environmental characteristics of candidate outpost sites. Site certification for human outposts requires a set of data about the specific site that can best be performed by surface investigations. Specific measurements are listed in other investigations.

<u>10. Investigation:</u> Determine the fate of typical effluents from human activities (gases, biological materials) in the Martian surface environment.

Measurements

a. Determine the rate of reaction of typical materials exposed to the Martian environment. *Technology development needed: Much.*

b. Monitor the rate of dispersion of analog materials in the Martian environment. *Technology development needed: Much.*

B. Objective: Conduct in situ engineering science demonstrations (priority order of investigations under review)

<u>1. Investigation:</u> Demonstrate terminal phase hazard avoidance and precision landing. Necessary to decrease the risks associated with soft landing, and to enable pinpoint landing. **Requires flight demonstration during terminal descent phase.**

Measurements

a. Demonstrate terrain recognition systems (e.g., LIDAR)

b. Utilize hazard avoidance algorithms during terminal descent.

c. Demonstrate controlled terminal descent and soft landing.

***<u>2. Investigation:</u>* Demonstrate mid-L/D aeroentry/aerocapture vehicle flight.** Mid-L/D (0.4–0.8) aeroentry shapes will be required as payload masses increase. Mid-L/D aeroassist increases landed vehicle performance and landing precision. **Requires wind tunnel testing and flight demonstration during aeroentry phase of the mission.**

Measurements

a. Flight test slender body, mid L/D (0.4–0.8) aeroentry shapes.

b. Achieve and verify an actual horizontal position error at parachute deployment of ±10 km or less. This value includes an entry aero-maneuvering control error goal of ±2 km error, the Mars approach phase navigation error, map tie errors, parachute deployment variables, etc.

c. Use approach navigation that provides control of the flight path angle at the defined entry interface to ±0.5 deg or less and pre-entry knowledge of ±0.1 deg or less.

d. provide control to remain well within the expected control authority of the entry aero-maneuvering system and the knowledge is needed to provide initiation of the entry aero-maneuvering system IMU.

e. The ability to obtain this approach navigation performance with radio navigation depends on selection of a low-latitude landing site location (latitude between 30 deg N and 30 deg S). High-latitude sites would require optical approach navigation.

f. Reconstruct the entry trajectory (after the fact) to an accuracy of ±1 km or better to provide verification of the entry aero-maneuvering system performance.

g. Demonstrate aerocapture maneuver in the Martian atmosphere at speeds within the envelope for human missions (5.7–8.7 km/sec in reference mission).

h. Collect vehicle attitude, trajectory, guidance and control system performance data, and free stream conditions for entire aeropass (atmospheric entry through heat shield ejection).

i. Collect heatshield performance for use in CO_2 chemistry model validation, predictions of aerothermal loads and thermal protection system response.

j. Collect temperatures at selected points within and on heat shield.

k. Collect pressure at selected points on the body.

l. Validation of flight trajectory determination vs. prediction, including aerodynamic predictions and atmospheric modeling.

m. Analysis of the performance of the guidance and control system, including sensors, attitude control system, and CPU.

3. Investigation: ***Demonstrate high-Mach parachute deployment and performance.*** Higher-ballistic-coefficient entry vehicles will be result from flying more massive landers. This will result in higher parachute deploy speeds, which are beyond the qualification of current parachute systems. **Requires high-altitude Earth-based testing and flight demonstration during Mars entry phase.**

Measurements

a. Demonstrate and qualify parachute deploy in an expanded velocity regime (up to M=3.0).

b. Demonstrate parachute deploy characteristics in the flow field trailing a mid-L/D aeroentry vehicle.

4. Investigation: ***Demonstrate in situ propellant (methane, oxygen) production (ISPP) and in-situ consumables production (ISCP) (fuel cell reagents, oxygen, water, buffer gases).*** Components that directly interact with the Martian environment should be evaluated in a relevant environment to determine their performance. End-to-end performance may be evaluated by acquisition of local resources, processing, storage, and use of end products**. Requires process verification with in situ experiments.**

Measurements

a. Demonstrate the intake and adsorption of carbon dioxide from the Martian atmosphere.

b. Demonstrate thermal management concepts of heat transfer between the components of the ISPP plant as well as to the outside environment.

c. Monitor the performance degradation characteristics of advanced solar array and radiator concepts operated in the actual Mars environment.

d. Evaluate the functionality of electrostatically removing accumulated dust off the solar array.

e. Understand the characteristics of zirconia cells to generate propellant-grade oxygen.

f. Demonstrate “end-to-end” system-level operation of ISPP and ISCP processes, including acquisition of resources, chemical processing, storage of products, and demonstration-level use of the products.

g. Demonstrate ISCP, such as buffer gas (nitrogen and argon) or water extraction.

***5. Investigation:* Access and extract water from the atmosphere, soils, regolith, and Martian groundwater systems.** Water is a principal resource. Requires in situ operations to determine hydrologic characteristics of aquifers and aquicludes. **Requires subsurface drilling.**

Measurements

a. Demonstrate autonomous drilling operations on the Martian surface.

b. Demonstrate progressively deeper drilling, beginning with pilot drill demonstrations to tens of meters, and concluding with depths corresponding to subsurface aquifers.

c. Demonstrate extraction of water from subsurface aquifers.

d. Demonstrate the extraction of water from Martian permafrost layers.

e. Demonstrate the ability to extract potentially useful quantities of water from the atmosphere.

f. Demonstrate the extraction of water from Martian regolith (hydrated minerals).

***6. Investigation:* Demonstrate deep drilling.** The Martian subsurface will provide access to potential resources (e.g., water) as well as providing access to valuable scientific samples. **Requires landed demonstration.**

Measurements

a. Demonstrate autonomous drilling operations on the Martian surface.

b. Demonstrate progressively deeper drilling, beginning with pilot drill demonstrations to 10’s of meters, and concluding with depths corresponding to subsurface aquifers.

C. Objective: Emplace infrastructure for (future) missions (priority order of investigations under review)

1. High-capacity power systems to support ISPP activities in support of robotic sample return missions and eventual human support.

Performance Targets

a. 300 watts per kilogram solar power generation.

b. Megawatt-class surface nuclear power.

c. Megawatt-class space solar power arrays.

2. Communication infrastructure **to support robotic missions with high data rates or a need for more continuous communications, and eventual human support.**

Performance Targets

a. 1 Mb/sec bandwidth at maximum Earth-Mars distance.

b. 99% (TBD) communications link availability, other than during superior conjunction.

3. Navigation infrastructure to support precision landings for robotic or human missions.

Performance Targets

a. Provide navigation infrastructure that will support arriving Mars spacecraft multi-point tracking and nav state determination.

b. Provide navigation infrastructure that will support determination of surface spacecraft location to (TBD) meters.

Part 3:

The First Returned Martian Samples: Science Opportunities

by the Mars Sampling Advisory Group

Chair: Glenn MacPherson

Abstract

Mars sample return missions are expected to increase progressively in their sampling sophistication from one mission to the next. The first mission will likely include scoop and/or auger sampling tools on a fixed lander. The scientific potential of a sample collected only with such tools would be large, but it will be greatly enhanced if the sampling system has the specific capability to locate and acquire small rocks in addition to "fines" (grains <1–2 mm in diameter). Such a mixture of fines plus rocks (a *regolith sample*) would enable mineralogic, petrologic, isotopic (radiometric and cosmic-ray exposure age) studies that would provide greater insight into Martian crustal composition and evolution than permitted by fines samples alone. These studies will also address the conditions on Mars that may have been conducive to development of life. In addition, collected sedimentary rocks will provide the best chance of preserving evidence for any prebiotic compounds, biogenic traces, and aqueous activity, thus providing clues in the search for past and present life on Mars. The fines component will contain information on average crustal composition, chemical and physical weathering, and other geological surface processes, and will be critical for providing ground truth measurements for remote sensing data. A dedicated sample of Martian atmosphere will give important information about the evolution of the present atmosphere from its suspected original denser and wetter state. Thus, fines and rock fragments are essential to the first mission, and collecting an atmosphere sample as soon as possible is important. Subsequent sample collection missions should increase in capability, with improved mobility and greater capability to select samples on the basis of properties such as composition.

Preamble—The Scientific Imperative for Sample Return

The search for ancient or extant extraterrestrial life is one of the principal questions driving the Mars Exploration Program. This question is of fundamental importance not only to the scientific community but also to the public, as vividly demonstrated by the intense general and congressional interest following the publication of the paper by McKay et al. (1996) relating to the meteorite ALH84001. However, the results of that paper are regarded by many scientists as inconclusive, and the requirement to find more substantive proof—pro or con—of Martian life is intense. Short of photographing either a live creature moving across the Martian landscape or else an incontrovertible macrofossil, the only unambiguous means of addressing the question of Martian life is to study promising samples back on Earth. No robotic analytical measurements made on the Martian surface can give a result on this question beyond any controversy. For example, robotic measurements of key isotope ratios that are significantly affected by biogenic processes have a precision roughly comparable to the total range of the expected effects, and about one order of magnitude worse than laboratory measurements. The return of samples from multiple sites on Mars must occur if answering the question of Martian life remains a priority goal. Indeed, if no such missions occur, it will mean that goal has ceased to be a driving priority.

Early Mars sample return is necessary also to accomplish another important task, namely establishing "ground truth" about the nature and distribution of materials that comprise the Martian surface. Global exploration of Mars will necessarily be done by remote sensing means, especially from orbit. Experience from exploration of Earth's moon has demonstrated that proper interpretation of remote sensing data must be accompanied by the kind of detailed knowledge of lunar rocks and fines that was obtained by laboratory analysis of the Apollo and Luna materials. Conversely, the remote sensing data sets provided by the Clementine and Lunar Prospector missions put the Apollo and Luna mission samples in a global context. CAPTEM (the Curation and Analysis Planning Team for Extraterrestrial Materials) organized a series of workshops and an upcoming book that emphasize how valuable such an integrated program of remote sensing and sample analysis has been for the Moon (see the CAPTEM document at http://cass.jsc.nasa.gov/captem/). This approach can and should be applied to the exploration of Mars and other rocky bodies as well. Much of the Martian surface is covered with wind-blown dust. In addition, the rocks that are exposed at the surface may be coated with a weathering rind of unknown thickness that prevents their true underlying character from being determined either by orbital or in situ remote sensing. Rover-based robotic analytical methods cannot characterize either the weathering materials or their precursors with sufficient precision, or determine the precise spatial and chemical relationships between the two. Therefore, it is essential to an integrated program that the chemical and mineralogical composition of the Mars dust and weathering products from diverse sites be unambiguously established as early as possible, by analyzing returned samples in Earth laboratories. Once these properties are well known for a reasonable variety of Martian materials, the results from remote sensing and surface robotic methods can be interpreted with much greater confidence.

This document examines the scientific possibilities of the first returned Mars samples. Its authors strongly support the concept of an integrated and balanced Mars Exploration Program—one that combines the strengths of remote sensing, robotic surface exploration, sample return, and, eventually, human exploration. We also support a program in which the sophistication of sample collection improves from mission to mission. For reasons summarized above we believe that such a program will proceed most efficiently if some sample return begins early in the program. However, the critical point is that <u>multiple sample returns, from diverse sites, must ultimately take place</u> for the program to succeed in its stated goals.

Introduction

Beginning in mid-December 1999, the missions and other projects composing the Mars Exploration Program were re-examined and various options were considered for the development of a new integrated strategy. These considerations are continuing, with the goal of formulating a revised exploration plan by mid- to late-2000. One likely result of the recent rethinking of the Mars Program Architecture is that the first sample-return mission will be simpler than formerly planned. Despite the expected simplicity of the first sample collection mission, however, the scientific imperative for it to include fresh (unweathered) rocks remains. The purpose of this document is to reiterate the rationale for this need, so that the new program architecture can successfully accomplish the scientific goals.

The current exploration strategy for Mars is centered on three primary questions:

1. Did the necessary conditions for life exist in the earlier history of Mars, did life arise on Mars in the past, and does native Martian life exist today?
2. How did Mars evolve, with special emphasis on the long-term evolution of the Martian climate and atmosphere and the history and role of water?
3. What are the conditions and resources on Mars conducive for future human exploration?

Of these questions, those related to past or present Martian life have the highest priority to both the scientific community and the public. Exploration strategies that can best address these and related questions have been debated at length in the science community over the last decade. It is generally agreed that the search for evidence of past Martian life will be extremely challenging and will require a sustained and aggressive approach to locate sites where past environments might have sustained life and preserved evidence of it. The general Mars Exploration Program has been structured to obtain the scientific information needed to carry out such searches. Again drawing on the lunar experience, it is clear that successful robotic exploration to meet the program goals must include a careful balance of science based on orbital measurements (e.g., imaging, infrared spectroscopy, gamma ray spectroscopy, laser altimetry, etc.), in situ science from landers and/or rovers, and samples returned to Earth for laboratory study. All of these aspects of exploration are essential complementary parts of an integrated program for Mars exploration.

It also is generally agreed that the return to Earth of a scientifically selected and diverse suite of rock samples is required to maximize the possibility of finding preserved fossil or chemical traces of past life. In contrast, searching for present life will probably require deep drilling to penetrate through the inferred zone of surface oxidation down to depths where liquid water could exist. The likelihood that such deep drilling will be beyond the technological capabilities of surface robots provides an important scientific rationale for the human exploration of Mars. Thus, the Human Exploration and Development of Space (HEDS) activities will also play an important role in the early robotic phase of exploration by carrying out precursor experiments to evaluate the potential for future human exploration. HEDS precursor science (related to question 3, above) should be conducted in conjunction with higher-priority goals of exploring for life, and understanding the past volatile and climate history of Mars.

The Mars Exploration Program now taking shape will involve a sensible phased and integrated approach, with increasing technological complexity from mission to mission and including remote sensing, landed operations and rovers, sample returns, and eventual human exploration. Within the sample return component, the series of missions should likewise increase in their complexity, perhaps beginning with relatively simple sampling tools but culminating with samples collected during long forays by sophisticated rovers using devices capable of acquiring rock interiors.

In evaluating the scientific return that will be gained from samples acquired by the first mission, we assume that mission will be the *first in a series of* progressively more sophisticated missions as outlined above. Nevertheless, a major conclusion of this report is that the scientific return of the first mission will be greatly increased if some effort is made during spacecraft design to include the ability specifically to select and sample small rocks in addition to fines.

The Nature of Mars Surface Materials

A significant portion of the Martian surface is probably covered by *regolith*, which is composed of fragmental materials ranging from micrometer-sized dust through millimeter-sized grains (collectively called “fines”) to rocks that are meters or more in diameter. On the Moon, regolith deposits cover the surface, range in thickness from 2.5 to >16 m, and result principally from meteorite impact “gardening.” Lunar regolith samples made very significant contributions to the study of the Moon. While impact-generated regolith undoubtedly exists on Mars, its proportion relative to materials produced by other processes (e.g., erosion and weathering) is completely unknown.

Results from the Viking landers and Pathfinder suggest that Martian fines include (1) dust (particles a few microns in diameter) that settled from the atmosphere, (2) sand transported across the surface by wind, impact, and possibly water, and (3) materials developed in place by inferred weathering processes, forming duricrust, “clods,” and other products.

Viking IRTM data suggest that the Viking landing sites and the Pathfinder site are among the rockiest on Mars. Yet, even though numerous objects inferred to be rocks were seen at the Viking sites, all of the 0.2–1.2 cm-sized rock fragments collected within the 1.5 to 3 meter reach of the lander scoops turned out not to be rock but dirt clods. Moreover, Mars Global Surveyor images suggest that substantial parts of the Martian surface are mantled with presumed windblown material, including sand (evident in the abundant dune forms). Consequently, it is possible that landers with a limited sampling “reach” might collect *only* fines. Such material would have considerable scientific interest, but, as documented below, a combination of rock fragments and fines would give even greater scientific return.

The Science Payoff from Rock Fragments

Studies Related to the Search for Life

The unifying theme for all aspects of the Mars Exploration Program is "follow the water," and this is critical in the search for life and for the conditions for the development of life. Although the search for extant life must necessarily focus on finding contemporary water reservoirs, evidence of ancient life is likely to be found in places where water once resided but no longer does. Hydrous minerals, and veins or more extensive deposits of minerals such as carbonates and sulfates, are the signatures within rocks of ancient water reservoirs of some kind. This is one of the underlying assumptions of the studies involving Martian meteorites such as ALH84001. Such minerals might be present as individual particles within the regolith fines, but the context of the rocks within which they formed is no longer present. From the point of view of biology, therefore, the identification of hydrous minerals and chemical sediments is of great interest and importance not only as preservers of possible microfossils but also for the information they provide on the distribution and movement of ancient Martian water.

Living systems on Earth show distinctive isotopic fractionation patterns that can be used as evidence for biogenic activity. For example, carbon isotope fractionations observed in the 3.87 Ga Isua Formation of Greenland have been interpreted as the earliest chemical fossil signatures on Earth. Ignorance at present of the average crustal values for these isotopes on Mars has hampered the ability to interpret isotopic determinations of ALH84001 in such a context; isotopic measurements obtained from rock fragments within a returned regolith sample will provide that information.

Mars Crustal Evolution

Some of the most important observations that can only be obtained from rock fragments within a regolith sample are those that relate to the nature and evolution of the Martian crust. The rocks and minerals of the surface provide the primary record of geological processes and environments that have influenced the history of the planet. Unaltered igneous rocks in the regolith will yield invaluable information about magmatic processes, ages, and the tectonic history of the planet. The presence of any Martian metamorphic rocks would greatly revise our concepts about crustal processes and recycling on Mars. Melt glasses would provide information on impact processes, while primary aqueous sedimentary materials could provide insight into the role of water and the potential for life.

The only current sources of information about absolute ages of events on Mars are the radiometric ages derived from Martian meteorites. Radiogenic ages of a diversity of returned unweathered small rocks, determined using a variety of isotopic systems, would provide important insights into the history of Mars—including the process of differentiation into a crust, mantle, and core—and preliminary information about the rates and duration of geological processes, such as volcanism, impact cratering, and hydrological processes. Information about some of these processes, especially the cratering record, will be even more valuable if the rocks are collected from known geological contexts (e.g., derived from obvious nearby outcrops). Another particularly interesting issue is the age of the youngest volcanism on Mars. Some Martian meteorites give ages suggesting that volcanism on Mars might have been active as recently as approximately two hundred million years ago. Such young ages naturally suggest the possibility of modern volcanism. Apart from implications for the cooling history of Mars, such recent volcanism would increase the likelihood of contemporary hydrothermal activity, which could provide a hospitable environment for present life. It must be emphasized that isochron ages can only be measured on multiphase rocks, not individual minerals. If the grain sizes typical of Martian meteorites (generally larger than 0.2–0.3 mm) are indicative of Martian surface rocks, then unweathered rock fragments of several millimeters or more are required in order to enable mineral separates and still have material left over to make the petrologic studies necessary to put the ages in context. Should the rock samples brought back by the first sample return mission turn out to be completely weathered, then the scientific importance of using tools capable of sampling the interiors of large rocks on later missions will be much greater.

Mars Surface Evolution and Processes

All of the mineralogical data for Mars have been obtained from the Martian meteorites or from Earth-based or orbiter measurements. The Viking scoop experience with small "rocks" that crumbled persuaded many scientists that rocks on the Martian surface are heavily weathered. Yet, data from MGS that appear to indicate a lack of hydrous minerals, plus the low abundance of weathering products in Martian meteorites, together argue against this hypothesis. The collection of small rock fragments will likely settle this issue conclusively, especially if the fragments have cores of unaltered (primary) rock surrounded by their weathering rinds. Specific observations of any secondary alteration products and their relationship to individual primary minerals, down to the scale accessible by transmission electron microscopy, will permit quantitative assessment of specific weathering reactions, their rates, and the conditions under which they occurred. Such observations are important for future sampling strategies. For example, determination of weathering rind thickness and composition of Martian rocks will guide the design of more sophisticated sampling devices such as a rock corer.

Stable isotope studies (e.g., H, C, O, S, and the noble gases) of primary and secondary minerals in regolith rock samples will aid the understanding of crust-atmosphere interactions on Mars. Such measurements can provide crucial information for understanding the long-term climate history and atmospheric evolution of Mars. Finally, stable isotope data will provide ultimate confirmation (or not) for the Martian origin of the SNC meteorites that have been discovered on Earth.

The cosmic ray exposure history of the Martian surface is unknown. How long have the surface materials been exposed to cosmic rays and what fraction of the material found on the surface today has been recently exposed? The measurement of the effects of primary and secondary cosmic rays would permit the understanding of how aeolian (wind-driven), impact, fluvial, and other processes redistribute materials on the surface of Mars. Some information may also be gleaned about the intensity and rate of chemical and physical breakdown of rocks on the Martian surface.

Paleomagnetic Studies

The history of the magnetic field on Mars is likely to be closely linked to the history of planetary differentiation, rates of internal heat loss, and volcanism, as well as atmospheric evolution. Studies of potential magnetic minerals in rocks may provide important information about remanant magnetic properties of surface materials and (in association with radiometric dating constraints) how field strength has varied through time on Mars.

The Science Payoff from “Fines”

Samples consisting of particles smaller than 1–2 millimeters in diameter and/or cemented clods composed of such fines will provide clues to the weathering and erosion processes on Mars, and to the nature and origin of Martian regolith, thus enhancing future lander-based analysis. Most importantly, the fines will establish some necessary chemical and mineralogic “ground truth” for orbital remote sensing data. In general, fines samples will be more valuable if acquired away from the contaminating effects of lander exhaust.

Ground Truth for Remote Sensing Data

Current models and new Global Surveyor data suggest that significant portions of Mars’ surface are mantled with "fines" of mostly unknown thickness and composition, but which probably include dust settled from atmospheric suspension plus sand moved along the surface. Because most of our global studies of the Martian surface have been and will be done by remote sensing, especially from orbit, it is critical to establish unambiguously the physical, chemical, and mineralogic characteristics of the fines by laboratory analysis. Only with this kind of “ground truth” can the global chemical characteristics of the Martian surface be properly interpreted. Previously obtained data (e.g., Viking infrared thermal mapping spectra) as well as currently obtained data (e.g., MGS thermal emission spectrometer observations) are basically unconstrained by such ground truth. The fines recovered by an early sample return mission will be most important for the correct interpretation of past and future remote sensing data.

Mars Surface Processes

Determining the chemical and mineralogic composition of fines will provide some insight into Martian average crustal compositions and chemical weathering regimes. Most “fines” are probably reworked by the wind, but also could include materials physically weathered from bedrock exposures in geologically recent times. If the fines consist in part of the weathering products of primary rocks, then those products will provide some insight into both the parent materials and the nature of the weathering processes. Fines will also give insight into the relative contributions to the regolith from weathering, erosion, and impact processes. The trace element and isotopic composition of the mobile element component of the fines, mainly sulfur and chlorine, will provide clues to volcanic aerosol contributions, hydrothermal contributions, and even possible sources from evaporite deposits laid down in ancient seas.

The size, shape, and degree of sorting of fines, and surface textures of individual grains, could provide valuable information about the surface processes of erosion, transportation, and deposition on Mars, processes which at present are poorly understood. In addition, the surface textures of individual sand-size grains (as determined by, e.g., scanning electron microscopy) can provide insight into modes of transport (wind, water, and ice). Such information would contribute toward understanding the surface history of the landing site. For example, the chemical and mineralogical composition of dust settled from the atmosphere (and representing a global "homogenization") are unknown and will probably be distinctly different from the materials transported along the surface, which are likely to be derived from local or regional sources. In terms of human exploration objectives, an accurate assessment of particle size and chemical composition would be important for understanding the conditions for exploration of Mars by humans and, ultimately, long-term habitability. Dust properties are also important for the engineering of solar panels and other lander and rover subsystems. Although some technologies have been developed in which particle size distributions and surface textures might be determined by in situ experiments, such measurements are made more easily and more thoroughly on samples returned to Earth.

All sites visited thus far by landers show evidence for the formation of duricrust. The composition of potential sedimentary cements, the specific minerals involved in duricrust formation, and insight into how and when they were formed are basic issues that could be addressed with a sample of Martian "fines" (especially if the sample contained actual clods of the duricrust). In addition, understanding the precise chemistry of Martian fines will contribute to a HEDS goal of evaluating their toxicity or other possible biohazards that could affect astronauts.

Finally, if a fines sample can be sufficiently well preserved en route to Earth, there is some hope of identifying and characterizing the putative super oxidant identified by Viking.

The Search for Life

Like Earth, Mars experiences a constant infall of micrometeorites and interplanetary dust particles (IDPs), some of which (carbonaceous chondrites) contain as much as 1–3 wt. % carbon. Consequently, some residual carbon chemistry is expected to be present in Martian surface materials. Although the Viking experiments failed to detect carbon compounds in surface "fines" on Mars, they could be present in very low concentrations (<1.0 ppb). Returned samples would allow much higher sensitivity searches for and analyses of carbon and organic compounds, helping in turn to discriminate whether such materials are meteoritic or possibly biotic in origin.

The Science Payoff from an Atmosphere Sample

The Martian atmosphere probably was once warmer, denser, and wetter than it is at present. The best starting point for understanding what those ancient conditions were, and the processes by which the atmosphere evolved to its current state, is through precise analysis of stable isotopes of the gaseous species. Robotic measurements are too imprecise for this purpose; only laboratory analyses of a returned atmosphere sample—ideally, one collected in a dedicated sealed container designed solely for that purpose—can achieve the per-mill-levels of precision. In collecting such a sample, every effort should be made to minimize possible contamination from rocket exhaust and Earth atmosphere. Even if collection of such a sample is not possible on a first sample return mission, it must be a high priority for following missions.

Our interpretation of the provenance of Martian meteorites hinges on the putative identity of trapped meteoritic gases with the Martian atmosphere as measured by Viking. Again, a precise laboratory analysis of Martian atmosphere is essential.

Conclusions

The samples likely to be returned by the first Mars sample return mission will provide a wealth of scientific information that will be critical to properly plan future missions and evaluate their results. The anticipated science return depends on the type of materials collected. A sample containing rock fragments with unaltered cores will provide important information about the primary *geologic processes and history on Mars,* and also about climatic, hydrological, and weathering history. A sample consisting exclusively of fine-grained materials will provide information about modern climate, weathering processes, and surface composition and other properties of interest for evaluating *present surface conditions* on Mars. Such properties have implications for future human exploration. An atmosphere sample is essential for understanding the evolution of the Martian atmosphere to its current tenuous and dry state. The maximum scientific information will be assured by sample returns from multiple sites, which include fines, rock fragments, and atmosphere. Ideally, at least some of the rock fragments could be documented as coming from identifiable outcrops. Such a diverse assortment of samples would also most efficiently serve to guide future, more carefully targeted sample returns that will explore for a record of Martian life.

References

McKay, D.S. et al., *Science* **273**, p. 924 (1996).

Appendix 1
Group Member Lists

Mars Expeditions Strategy Group (MESG) Members

Dan McCleese, Chair	JPL
Mark Adler	JPL
Joe Boyce	NASA HQ
Geoff Briggs	NASA/Ames
Mike Carr	USGS
Ben Clark	Lockheed/Denver
Dave DesMarais	NASA/Ames
Mike Drake	U of AZ
Mike Duke	LPI
Jack Farmer	NASA/Ames
Jim Gooding	NASA/JSC
Norm Haynes	JPL
Noel Hinners	Lockheed/Denver
Dave Lavery	NASA HQ
Laurie Leshin	UCLA
Lynn Lowry	JPL
Jane Mellors	ESA
Michael Meyer	NASA HQ
Sylvia Miller	JPL
Toby Owen	U. of Hawaii
David Paige	UCLA
Lewis Peach	NASA HQ
Jeff Plescia	NASA HQ
Roald Sagdeev	Univ. Maryland
Steve Saunders	JPL
Everett Shock	Washington Univ.
Larry Soderblom	USGS
Sean Solomon	Carnegie Inst.
Steve Squyres	Cornell U.
Gregg Vane	JPL
Heinrich Waenke	Max Planck Inst.
Chuck Weisbin	JPL

Mars Exploration Payload Assessment Group (MEPAG) Members

Banerdt, B.	JPL
Bell, J.	Cornell
Bianchi, R.	CNR-IAS/Italy
Bibring, J.P.	IAS/France
Birk, J.L.	IPG/Paris
Briggs, G.	ARC/NASA
Calvin, W.	Univ. Nevada, Reno

Mars Exploration Payload Assessment Group (MEPAG) Members (cont'd)

Clark, B.	Lockheed-Martin
Connolly, J.	JSC/NASA
Coradini, A.	ENR-IAS/Italy
Counil, J.L.	CNES/France
Drake, M.	Univ. Arizona
Duke, M.	Lunar Planet. Institute
Farmer, J.	Ariz. State Univ.
Flamini, E.	ASI/Italy
Golombek, M.	JPL
Greeley, R.	Ariz. State Univ.
Haberle, R.	ARC/NASA
Howard, A.	U. Virginia
Jakosky, B.	Univ. Colorado, Boulder
Kendall, D.	CSA/Canada
MacPherson, G.	Smithsonian Institute
McKay, D.	JSC/NASA
Raulin, F.	LISA/CNRS-Univ. Paris
Rocard, F.	CNES-Paris
Sanders, J.	JSC/NASA
Sotin, C.	Univ. Nantes/France
Squyres, S.	Cornell University
Sullivan, T.	JSC/NASA
Taylor, J.	Univ. Hawaii
Waenke, H.	MPIC Mainz/Germany
Zent, A.	ARC/NASA

Mars Sampling Advisory Group Members

J. Bibring, CNES, Paris, France
J. Crisp, JPL, Pasadena, CA
D. DesMarais, NASA Ames Research Center, Mountain View, CA
M. Drake, University of Arizona, Tucson, AZ
J. Farmer, Arizona State University, Tempe, AZ
R. Greeley, Arizona State University, Tempe, AZ
L. Leshin, Arizona State University, Tempe, AZ
G. MacPherson, Smithsonian Institution, Washington, DC
K. Nealson, Jet Propulsion Laboratory, Pasadena, CA
J. Papike, University of New Mexico, Albuquerque, NM
D. Papanastassiou, Jet Propulsion Laboratory, Pasadena, CA
S. Squyres, Cornell University, Ithaca, NY
G. Taylor, University of Hawaii, Honolulu, HI

Mars Ad Hoc Science Team (MAST) Members

McCleese, D. (Chair)	JPL
Arvidson, R.	Wash. Univ.
Carr, M.	USGS
Drake, M.	Univ. Ariz.
Farmer, J.	Ariz. State Univ.
Garvin, J.	NASA/HQ
Greeley, R.	Ariz State Univ.
McSween, H.	Univ. Tenn.
Soderblom, L.	USGS

Appendix 2
MEPAG Meeting Attendee Lists

Participants in the MEPAG/Mars Peer Review Group meeting, 22–24 February 2000
(* MEPAG Member)

Agee, C.	JSC/NASA
Ahlf, P.	NASA HQ
Angrilli, F.	CISAS-UNIPD
Arivdson, R.	Wash. Univ.
*Banerdt, B.	JPL
Barengoltz, J.	JPL
Beaty, D.	JPL
*Bell, J.	Cornell
Benner, S.	Univ. of Florida
*Bianchi, R.	CNR-IAS/Italy
*Bibring, J.P.	IAS/France
*Birk, J.L.	IPG/Paris
Blaney, D.	JPL
Blamont, J.	CNES/JPL
Bonneville, R.	CNES/France
Bourke, R.	JPL
*Briggs, G.	ARC/NASA
Budney, C.	JPL
*Calvin, W.	Univ. Nevada, Reno
Campbell, J.	JPL
Cazaux, C.	CNES/France
Christensen, P.	Ariz. State Univ.
*Clark, B.	Lockheed-Martin
*Connolly, J.	JSC/NASA
Cook, R.	JPL
*Coradini, A.	ENR-IAS/Italy
*Counil, J.L.	CNES/France
Crisp, J.	JPL
Cutts, J.	JPL
d'Uston, C.	CESR/Toulouse
Debei, S.	CISAS
*Drake, M.	Univ. Arizona
*Duke, M.	Lunar Planet. Institute
Edwards, C.	JPL
Elachi, C.	JPL
Espinasse, S.	ASI/Italy
*Farmer, J.	Ariz. State Univ.
*Flamini, E.	ASI/Italy
Gavin, T.	JPL
Gershman, B.	JPL
Goldstein, B.	JPL
*Golombek, M.	JPL
Granham, J.	JPL
Grant, J.	NASA HQ
*Greeley, R.	Ariz. State Univ.
*Haberle, R.	ARC/NASA
Hale, W.	JSC/NASA
*Howard, A.	U. Virginia
Hubbard, S.	ARC/NASA
Hum, B.	CSA/Canada
*Jakosky, B.	Univ. Colorado, Boulder
Jones, C.	JPL
Jordan, F.	JPL
*Kendall, D.	CSA/Canada
Kohlhase, C.	JPL
Leshin, L.	Ariz. State Univ.
Liebrecht, P.	GSFC/NASA
Lunine, J.	Univ. Arizona
McCleese, D.	JPL
*McKay, D.	JSC/NASA
MacPherson, G.	Smithsonian
Morrision, A.	JPL
Mugnuolo, R.	ASI/Italy
Nealson, K.	JPL
O'Neil, B.	JPL
Olivieri, A.	ASI/Italy
Paige, D.	UCLA
Palluconi, F.	JPL
Papanastassiou, D.	JPL
Papike, J.	Univ. of New Mexico
Pate-Cornell, E.	Stanford
Peach, L.	NASA HQ
Piccioni, G.	CNR-IAS/Italy
Pilcher, C.	NASA HQ
Race, M.	SETI
*Raulin, F.	LISA/CNRS-Univ. Paris
*Rocard, F.	CNES-Paris
Roncoli, R.	JPL
Rosell, S.	JPL
Rummel, J.	NASA HQ
*Sanders, J.	JSC/NASA
Saunders, M.	LARC/NASA
Saunders, S.	JPL
Schmidt, R.	ESA/ESTEC
Seidel, D.	JPL
Senske, D.	JPL
*Sotin, C.	Univ. Nantes/France
*Squyres, S.	Cornell University
Stabekis, P.	Lockheed-Martin/ NASA HQ

*Sullivan, T.	JSC/NASA	Whiteley, J.	JSC/NASA
*Taylor, J.	Univ. Hawaii	Wilson, M.	JPL/CNES Liaison
Theisinger, P.	JPL	Yarnell, N.	JPL
Thompson, T.	JPL	*Zent, A.	ARC/NASA
*Waenke, H.	MPIC Mainz/Germany	Zimmerman, J.	ISS/JPL
Weisbin, C.	JPL	Zurek, R.	JPL
Weitz, C.	NASA/HQ		

Participants at the MEPAG meeting, 8–10 August 2000
(* MEPAG Member)

*Banerdt, B.	JPL	McCleese, D.	JPL
Beaty, D.	JPL	Morrison, A.	JPL
Berinstain, A.	CSA/Canada	Naderi, F.	JPL
Betts, B.	NASA HQ	Nealson, K.	JPL
Blacic, J.	Los Alamos	*Niehoff, J.	SAIC
Blaney, D.	JPL	Orosei, R.	CNR/Italy
*Briggs, G.	ARC/NASA	Paige, D.	UCLA
Budney, C.	JPL	Palluconi, F.	JPL
*Carr, M.	USGS	Papanastassiou, D.	JPL
Christensen, P.	Ariz. State Univ.	Pate-Cornell, E.	Stanford
*Clark, B.	Lockheed-Martin	Peach, L.	NASA HQ
*Connolly, J.	JSC/NASA	Phillips, M.	JPL
Dawson, S.	JPL	Pilcher, C.	NASA HQ
*Duke, M.	Lunar Planet. Institute	Riegler, G.	NASA HQ
Espinasse, S.	ASI/Italy	*Rogers, B.	Self
*Farmer, J.	Ariz. State Univ.	Saunders, S.	JPL
Friedman, L.	Planetary Society	Schmidt, R.	ESA/ESTEC
*Greeley, R.	Ariz. State Univ.	Senske, D.	JPL
Horttor, R.	JPL	*Sotin, C.	Univ. Nantes/France
*Howard, A.	U. Virginia	*Sullivan, T.	JSC/NASA
Hubbard, S.	NASA HQ	*Taylor, J.	Univ. Hawaii
*Jakosky, B.	Univ. Colorado, Boulder	Thompson, T.	JPL
		Viotti, M.	JPL
Jones, J.	JSC/NASA	*Waenke, H.	MPIC Mainz/Germany
Kohlhase, C.	JPL	Weitz, C.	NASA/HQ
Leshin, L.	Ariz. State Univ.	Zurek, R.	JPL
*MacPherson, G.	Smithsonian		

Participants at the MEPAG meeting, 15-17 November 2000
(* MEPAG Member)

Agee, C.	JSC
Allen, C.	JSC
*Arvidson, R.	Wash. Univ.
Beaty, D.	JPL
*Bianchi, R.	CNR IAS
*Bibring, J.P.	IAS
Blaney, D.	JPL
*Briggs, G.	ARC/NASA
Campbell, J.	JPL
*Carr, M.	USGS
*Christensen, P.	Ariz. State Univ.
Coradini, M.	ESA HQ
*Counil, J.L.	CNEC
Clifford, S.	LPI
Cutts, J.	JPL
Dawson, S.	JPL
Dolgin, B.	JPL
*Duke, M.	LPI
*Farmer, J.	Ariz. State Univ.
Gershman, B.	JPL
*Golombek, M.	JPL
*Greeley, R.	Ariz. State Univ.
Hoffmann, H.	DLR
Hubbard, S.	NASA HQ
Jordan, F.	JPL
*Kendall, D.	CSA
Kohlhase, C.	JPL
Lavery, D.	NASA HQ
Lindstrom, D.	JSC
*MacPherson, G.	Smithsonian
Martin, G.	NASA HQ
Matousek, S.	JPL
McCleese, D.	JPL
*McKay, D.	JSC
Miller, S.	JPL
Morrison, A.	JPL
Mugnuolo, R.	ASI
Naderi, F.	JPL
*Niehoff, J.	SAIC
Olivieri, A.	ASI
*Paige, D.	UCLA
Palluconi, F.	JPL
Papanastassiou, D.	JPL
Parrish, J.	NASA HQ
Pate-Cornell, E.	Stanford
Peach, L.	HEDS/USRA
Piccioni, G.	CNR-IAS
Plaut, J.	JPL
Pline, A.	NASA HQ
*Raulin, F.	LISA
Reiter, D.	Stanford
Rummel, J.	NASA HQ
Saunders, S.	JPL
Senske, D.	NASA HQ
Soffen, G.	GSFC
Stabekis, P.	Lockheed Martin
Thompson, T.	JPL
*Van Dover, C.	College of William & Mary
Vane, G.	JPL
Viotti, M.	JPL
*Waenke, H.	MPIC Mainz/Germany
Yen, A.	JPL
*Zent, A.	NASA ARC
Zimmerman, J.	Intl. Sp. Svcs.
Zurek, R.	JPL

Science Goals. The Mars Exploration Program studies Mars as a planetary system in order to understand the formation and early evolution of Mars as a planet, the history of geological processes that have shaped Mars through time, the potential for Mars to have hosted life, and the future exploration of Mars by humans. The strategy has evolved as we have learned more about Mars and as more questions have arisen.Â Astrobiology is a relatively new field of study, where scientists from a variety of disciplines (astronomy, biology, geology, physics, etc.) work together to understand the potential for life to exist beyond Earth. However, the exploration of Mars has been intertwined with NASAâ€™s search for life from the beginning. This image of Victoria Crater in the Meridiani Planum region of Mars was taken by the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter. Image credit: NASA/JPL-Caltech/University of Arizona.Â NASA has successfully tested components for a nuclear fission system it calls KRUSTY and officials said Thursday that full-power tests planned for March could clear the way for long-duration missions to Mars and other destinations. Developed under.Â Citizen scientists discover landform on Mars spot 'spiders' formation. We are on the verge of confirming alien life in the solar system, according to NASA chief scientist Ellen Stofan. The Mars Exploration Study Project was undertaken to establish a vision for the human exploration of Mars that would serve as a mechanism for understanding the. programmatic and technical requirements that would be placed on existing and planned Agency programs. In August 1992, the first workshop of the Mars Study Team held at the Lunar and Planetary Institute in Houston, Texas, addressed the â€œwhysâ€ of Mars exploration to provide the top-level requirements from which the Mars exploration program could be built (Duke and Budden 1992).