Part 3:

The First Returned Martian Samples: Science Opportunities

by the Mars Sampling Advisory Group

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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).