News and Views

Science Priorities for Mars Sample Return

The MEPAG Next Decade Science Analysis Group

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Acronym Glossary

AMS	Accelerator Mass Spectrometer
APXS	Alpha Proton X-ray Spectrometer
ARC	Ames Research Center
COSPAR	Committee on Space Research
EDL	Entry, Descent, and Landing, a critical phase for martian landers
EDX	Energy Dispersive Analysis
EMPA	Electron Microprobe Analysis
ExoMars	A rover mission to Mars planned by the European Space Agency
FTIR	Fourier Transform Infrared
GC	Gas Chromatograph
GCR	Galactic Cosmic Rays
GSFC	Goddard Space Flight Center
ICP	Inductively Coupled Plasma
IMEWG	International Mars Exploration Working Group
IMU	Inertial Measurement Unit
INAA	Instrumental Neutron Activation Analysis
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LC	Liquid Chromatography
LaRC	Langley Research Center
LD-BH	Life-detection and Biohazard Testing; used in the context of the test protocol
LPI	Lunar and Planetary Institute
MAV	Mars Ascent Vehicle, the rocket that would lift the samples off the martian surface
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover, a NASA mission launched in 2003
MEX	Mars Express, a 2003 mission of the European Space Agency
MI	Microscopic Imager, an instrument on the 2003 MER mission
MOD	Mars Organic Detector
MOMA	Mars Organic Molecule Analyzer, an instrument proposed for the 2013 ExoMars mission
MRO	Mars Reconnaissance Orbiter, a 2005 mission of NASA
MS	Mass Spectrometer
MSL	Mars Science Laboratory, a NASA mission to Mars scheduled to launch in 2009
MSR	Mars Sample Return

ND-MSR SAG Next Decade Mars Sample Return Science Analysis Group (also abbreviated as ND-SAG)
PCR Polymerase Chain Reaction
PE Preliminary Examination
PI Principal Investigator
PLD Polar Layered Deposits
RAT Rock Abrasion Tool, an instrument on the MER mission
SAM Surface Analysis at Mars, an instrument on the 2009 MSL mission
SEM Scanning Electron Microscope
SIMS Secondary Ion Mass Spectrometer
SMD Science Mission Directorate
SRF Sample-Receiving Facility
SSG Science Steering Group, a MEPAG subcommittee
STEM Scanning Transmission Electron Microscope
SwRI Southwest Research Institute
TBR To Be Reviewed
TEM Transmission Electron Microscope
TIMS Thermal Ionization Mass Spectrometer
TOF-SIMS Time-of-Flight Secondary Ion Mass Spectrometer
USGS US Geological Survey
VNIR Visible/Near Infrared
VS Vertical Surveys
XANES X-ray Absorption Near Edge Structure
XRD X-Ray Diffraction, a generic method for determining mineralogy
XRF X-Ray Fluorescence, a generic method for determining sample chemistry

I. Executive Summary

THE RETURN OF MARTIAN SAMPLES TO EARTH has long been recognized as an essential component of a cycle of exploration that begins with orbital reconnaissance and *in situ* surface investigations. Major questions about life, climate, and geology require answers from state-of-the-art laboratories on Earth. Spacecraft instrumentation cannot perform critical measurements such as precise radiometric age dating, sophisticated stable isotopic analyses, and definitive life-detection assays. Returned sample studies could respond radically to unexpected findings, and returned materials could be archived for study by future investigators with even more capable laboratories. Unlike martian meteorites, returned samples could be acquired with known context from selected sites on Mars according to the prioritized exploration goals and objectives.

The ND-MSR-SAG formulated the following 11 high-level scientific objectives that indicate how a balanced program of ongoing MSR missions could help to achieve the objectives and investigations described by MEPAG (2006).

(1) Determine the chemical, mineralogical, and isotopic composition of the crustal reservoirs of carbon, nitrogen, sulfur, and other elements with which they have interacted and characterize carbon-, nitrogen-, and sulfur-bearing phases down to submicron spatial scales in order to document processes that could sustain habitable environments on Mars both today and in the past.

(2) Assess the evidence for prebiotic processes, past life, and extant life on Mars by characterizing the signatures of these phenomena in the form of structure/morphology, biominerals, organic molecular and isotopic compositions, and other evidence within their geologic contexts.

(3) Interpret the conditions of martian water-rock interactions through the study of their mineral products.

(4) Constrain the absolute ages of major martian crustal geologic processes, including sedimentation, diagenesis, volcanism/plutonism, regolith formation, hydrothermal alteration, weathering, and cratering.

(5) Understand paleoenvironments and the history of near-surface water on Mars by characterizing the clastic and chemical components, depositional processes, and post-depositional histories of sedimentary sequences.

(6) Constrain the mechanism and timing of planetary accretion, differentiation, and the subsequent evolution of the martian crust, mantle, and core.

(7) Determine how the martian regolith was formed and modified and how and why it differs from place to place.

(8) Characterize the risks to future human explorers in the areas of biohazards, material toxicity, and dust/granular materials and contribute to the assessment of potential *in situ* resources to aid in establishing a human presence on Mars.

(9) For the present-day martian surface and accessible shallow subsurface environments, determine the preservation potential for the chemical signatures of extant life and prebiotic chemistry by evaluating the state of oxidation as a function of depth, permeability, and other factors.

(10) Interpret the initial composition of the martian atmosphere, the rates and processes of atmospheric loss/gain over geologic time, and the rates and processes of atmospheric exchange with surface condensed species.

(11) For martian climate-modulated polar deposits, determine their age, geochemistry, conditions of formation, and evolution through the detailed examination of the

composition of water, CO_2, and dust constituents, as well as isotopic ratios and detailed stratigraphy of the upper layers of the surface.

MSR would attain its greatest value if samples are collected as sample suites that represent the diversity of the products of various planetary processes. *Sedimentary materials* likely contain complex mixtures of chemical precipitates, volcaniclastics, impact glass, igneous rock fragments, and phyllosilicates. Aqueous sedimentary deposits are important for performing measurements of life detection, observations of critical mineralogy and geochemical patterns, and trapped gases. On Earth, *hydrothermally altered rocks* can preserve a record of hydrothermal systems that provided water, nutrients, and chemical energy necessary to sustain microorganisms. They also might have preserved fossils in their mineral deposits. Hydrothermal processes alter the mineralogy of crustal rocks and inject CO_2 and reduced gases into the atmosphere. Chemical alteration that occurs at near-surface ambient conditions (typically $< \sim 20°C$) creates *low-temperature altered rocks* and includes, among other things, aqueous weathering and various nonaqueous oxidation reactions. Understanding the conditions under which alteration proceeds at low temperatures would provide important insight into the near-surface hydrological cycle, including fluid/rock ratios, fluid compositions (chemical and isotopic, as well as redox conditions), and mass fluxes of volatile compounds. *Igneous rocks* are expected to be primarily lavas and shallow intrusive rocks of basaltic composition. They are critical for investigations of the geologic evolution of the martian surface and interior because their geochemical and isotopic compositions constrain both the composition of mantle sources and the processes that affected magmas during generation, ascent, and emplacement. *Regolith* samples (unconsolidated surface materials) record interactions between crust and atmosphere, the nature of rock fragments, fine particles that have been moved over the surface, exchange of H_2O and CO_2 between near-surface solid materials and the atmosphere, and processes that involve fluids and sublimation. Regolith studies would help facilitate future human exploration by assessing toxicity and potential resources. *Polar ices* would constrain present and past climatic conditions and help elucidate water cycling. Surface ice samples from the Polar Layered Deposits (PLD) or seasonal frost deposits would help to quantify surface/atmosphere interactions. Short cores could help to resolve recent climate variability. *Atmospheric gas* samples would constrain the composition of the atmosphere and processes that influenced its origin and evolution. Trace organic gases (*e.g.*, methane and ethane) could be analyzed for abundances, distribution, and relationships to a potential martian biosphere. Returned atmospheric samples that contain Ne, Kr, CO_2, CH_4, and C_2H_6 would confer major scientific benefits. Chemical and mineralogical analyses of martian *dust* would help to elucidate the weathering and alteration history of Mars. Given the global homogeneity of martian dust, a single sample is likely to be representative of the planet. A *depth-resolved suite* of samples should be obtained from depths that range from cm to several m within regolith or from rock outcrop to investigate trends in the abundance of oxidants (*e.g.*, OH, HO_2, H_2O_2, and peroxy radicals), the effects of radiation, and the preservation of organic matter.

Other sample suites include *impact breccias* that might sample rock types that are otherwise not available locally, *tephra* consisting of fine-grained regolith material or layers and beds possibly delivered from beyond the landing site, and *meteorites* whose alteration history could provide insights into martian climatic history.

The following factors would affect our ability to achieve MSR's scientific objectives:

(1) *Sample size.* A full program of scientific investigations would likely require samples of ≥ 8 g for bedrock, loose rocks, and finer-grained regolith. To support required biohazard testing, each sample requires an additional 2 g, leading to an optimal size of 10 g. Textural studies of some rock types might require one or more larger samples of ~ 20 g. Material should remain to be archived for future investigations.

(2) *Number of samples.* Studies of differences between samples could provide more information than detailed studies of a single sample. The number of samples needed to address MSR scientific objectives effectively is 35 (28 rock, 4 regolith, 1 dust, 2 gas). If the MSR mission recovers the MSL cache, it should also collect 26 additional samples (20 rock, 3 regolith, 1 dust and 2 atmospheric gas). The total mass of these samples is expected to be about 345 g (or 380 g with the MSL cache). The total returned mass with sample packaging would be about 700 g.

(3) *Sample encapsulation.* To retain scientific value, returned samples must not commingle, each sample must be linked uniquely to its documented field context, and rocks should be protected against fragmentation during transport. A smaller number or mass of carefully managed samples is far more valuable than a larger number or mass of poorly managed samples. The encapsulation of at least some samples must retain any released volatile components.

(4) *Diversity of the returned collection.* The diversity of returned samples must be commensurate with the diversity of rocks and regolith encountered. This guideline substantially influences landing site selection and rover operation protocols. It is scientifically acceptable for MSR to visit only a single site, but visiting 2 independent landing sites would be much more valuable.

(5) In situ *measurements for sample selection and documentation of field context.* Relatively few samples could be returned from the vast array of materials the MSR rover would encounter; thus we must be able to choose wisely. At least 3 kinds of *in situ* observations are needed (color imaging, microscopic imaging, and mineralogy measurement) and possibly as many as 5 (also elemental analysis and reduced-carbon analysis). No significant difference exists in the observations needed for sample selection vs. sample documentation. Revisiting a previously occupied site *might* result in a reduction in the number of instruments.

(6) *Surface operations.* To collect the samples required by MSR objectives, the lander must have significant surface mobility and the capability to assess and sample the full diversity of materials. Depending on the geology of the site, at least 6–12 months of surface operation would be required to explore a site and assess and collect a set of samples.

(7) *Sample acquisition system.* This system must sample weathered exteriors and unweathered interiors of rocks, as well as continuous stratigraphic sequences of outcrops that might vary in their hardness. Further, the system must have the capability to relate the orientation of sample structures and textures to those in outcrop surfaces, bedding planes, stratigraphic sequences, and regional-scale structures, and maintain the structural integrity of samples. A mini-corer and a scoop are the most important collection tools. A gas compressor and a drill have lower priority but are needed for certain samples.

(8) *Sample temperature.* Some key species (*e.g.*, organics, sulfates, chlorides, clays, ice, and liquid water) are sensitive to temperatures above surface temperatures. Objectives could most confidently be met if samples are kept below −20°C and with less confidence if they are below +20°C. Significant loss, particularly to biological studies, occurs if samples reach +50°C for 3 hours. Temperature monitoring during return would allow any changes to be evaluated.

(9) *Planning considerations involving the MSL/ExoMars caches.* Retrieving the MSL or ExoMars cache might alter other aspects of the MSR mission. However, given the limitations of the MSL cache, differences in planetary protection requirements for MSL and MSR, the possibility that the cache might not be retrievable, and the potential for MSR to make its own discoveries, the MSR rover should be able to characterize and collect at least some of the returned samples.

(10) *Planetary protection.* A scientifically compelling first MSR mission does not require the capability to access and sample a special region, defined as a region within which terrestrial organisms may propagate. Unless MSR could land poleward of 30° latitude, access rough terrain, or achieve significant subsurface penetration (>5 m), MSR is unlikely to be able to use incremental special regions capabilities. Planetary protection draft test protocols should be updated to incorporate advances in biohazard analytical methods. Statistical principles governing mass requirements for subsampling returned samples for these analyses should be reassessed.

(11) *Contamination control.* Inorganic and organic contamination must be minimized in order to achieve MSR scientific objectives. A study is needed to specify sample cleanliness thresholds that must be attained during sample acquisition and processing.

II. Introduction

Since the dawn of the modern era of Mars exploration, the return of martian samples to Earth has been recognized as an essential component of a cycle of exploration that began with orbital reconnaissance and *in situ* surface investigations (see, for example, the discussion of sample return in 3 decades of reports by the National Research Council (*e.g.*, National Research Council, 1978, 1990a, 1990b, 1994, 1996, 2001, 2007). Global reconnaissance and surface observations have "followed the water" and revealed a geologically diverse martian crust that could have sustained near-surface habitable environments in the distant past. However, major questions about life, climate, and geology remain; and many of these require answers that only Earth-based state-of-the-art analyses of samples could provide. This stems from the fact that flight instruments cannot match the adaptability, array of sample-preparation procedures, and micro-analytical capability of Earth-based laboratories (Gooding *et al.*, 1989). For example, analyses conducted at the submicron scale were crucial for investigating the ALH84001 meteorite, and they would be essential for interpreting the returned samples. Furthermore, spacecraft instrumentation simply cannot perform certain critical measurements, such as precise radiometric age dating, sophisticated stable isotopic analyses, and comprehensive life-detection experiments. If returned samples yield unexpected findings, subsequent investigations could be adapted accordingly. Moreover, portions of returned samples could be archived for study by future generations of investigators using ever-more-powerful instrumentation.

Some samples from Mars are available for research on Earth in the form of the martian meteorites. The martian meteorites, while indeed valuable, provide a limited view of martian geologic processes. These samples are all igneous in nature and minimally altered; thus they do not record the history of low-temperature water-based processes. These samples certainly do not represent the most promising habitable environments (Gooding *et al.*, 1989), and it is possible that the most extensively water-altered materials might be too fragile to survive an interplanetary journey. Most meteorites have young crystallization ages less than 1.3 billion years, which indicates that they represent only the most recent igneous activity on Mars (Borg and Drake, 2005). Their geochemical characteristics suggest that they are closely related to one another and are consequently not representative of all the lithologic and geochemical diversity that is likely to be present in an igneous martian rock suite (Borg and Draper, 2003; Borg *et al.*, 2003; Symes *et al.*, 2008). Because the meteorites arrived by natural processes and lack geologic context, it is extremely difficult to extrapolate the results from geologic studies of these samples to rocks observed from space or on the martian surface by landed spacecraft. In contrast, returned samples could be obtained from sites within a known geologic context and selected in order to achieve the goals and objectives of the Mars exploration community. Nevertheless, sample-return missions must surmount key challenges, such as engineering complexity, cost, and planetary protection concerns, before their enormous potential could be recognized. This document is intended to define this critical step forward toward realizing the enormous potential of Mars sample return.

On July 10, 2007, Dr. Alan Stern, Associate Administrator for the Science Mission Directorate (SMD), described to the participants of the 7th International Conference on Mars his vision of achieving Mars Sample Return (MSR) no later than the 2020 launch opportunity. He requested that the financial attributes, scientific options/issues/concerns, and technology development planning/budgeting details of this vision be analyzed over the next year. The Mars Exploration Program Analysis Group (MEPAG) is contributing to this effort by preparing this analysis of the science components of MSR and its programmatic context. To this end, MEPAG chartered the Next Decade MSR Science Analysis Group (ND-MSR-SAG) to complete 4 specific tasks:

(1) Analyze what critical Mars science could be accomplished in conjunction with, and complementary to, a next decade MSR mission.
(2) Evaluate the science priorities associated with guiding the makeup of the sample collection to be returned by MSR.
(3) Determine the dependencies of mobility and surface lifetime of MSR on the scientific objectives, sample acquisition capability, diagnostic instrument complement, and number and type of samples.
(4) Support MSR science planning as requested by the International Mars Exploration Working Group (IMEWG) MSR study. The charter is presented in Appendix I.

The return of any reasonable sample mass from Mars would significantly increase our understanding of atmospheric, biologic, and geologic processes occurring there, as well as permit evaluation of the hazards to humans on the surface. This is largely independent of how the samples are selected, collected, and packaged for return, and stems from the fact that there are no analogous samples on Earth. Thus, a mission architecture in which a limited number of surface samples are collected in a minimum amount of geologic context has been recommended in the past and has huge scientific merit (*e.g.*, MacPherson *et al.*, 2005). It is also important to realize that a significantly greater scientific yield would result from samples that are more carefully selected. Analytical results from samples that are screened, placed in detailed geologic context, collected from numerous locations and environments, and packaged and transported under conditions that more closely approximate those encountered on the martian surface would dramatically clarify the picture of Mars derived from the mission, as well as allow analytical results to be more rigorously extrapolated to the planet as a whole. As a consequence of these facts, this document outlines a sampling strategy that is necessary to *maximize* scientific yield. The inability to complete all the surface operations associated with this sampling strategy by no means negates the usefulness of these samples. Rather, it results in a proportional loss of scientific yield of the mission. Thus, this study is expected to constitute input to a Mars program architecture trade analysis between scientific yield and cost.

III. Evaluation Process

Prior to beginning this study, the ND-SAG was briefed on the conclusions of the NASA Mars Sample Return Science Steering Group II (MacPherson *et al.*, 2005; Appendix III) and the National Research Council Committee on an Astrobiology Strategy for the Exploration of Mars. These reports document the importance of sample return in a complete strategy for the exploration of Mars, and many of their conclusions are reiterated here. However, the current analysis has benefited from discoveries made in the interval since these reports were written, such as phyllosilicates, silica, and the distribution and context of polyhydrated sulfates on the surface of Mars. It is expected that some of the conclusions of this report will be further elucidated and strengthened as results from Phoenix, MSL, and ExoMars become available. This may be particularly true of the results from analyses of organic matter and ices.

Assumptions used in this study are:

(1) The sample return mission would begin in either 2018 or 2020.
(2) MSL will launch in 2009 and will prepare a rudimentary cache of samples that would be recoverable by the MSR mission. ExoMars would carry a similar cache.
(3) The functionality of sample acquisition associated with MSR would be independent of MSL. This functionality may either be landed at the same time as the sample return element of MSR, or it may be separated into a precursor mission.
(4) The Mars Exploration Program would maintain a stable program budget of about $625 million per year that grows at 2% per year.

To complete these tasks and link strongly the report of the ND-SAG to the MEPAG Goals Document, the ND-SAG was divided into 4 subteams that correspond to each of the 4 main MEPAG goals. The goals, as outlined in the Goals Document, are: determine whether life ever arose on Mars, understand the processes and history of climate on Mars, determine the evolution of the surface and interior of Mars, and prepare for human exploration. Each group examined the individual investigations outlined in the MEPAG Goals Document and considered the following:

• Whether sample return would facilitate the investigation.
• The type, mass, number, and diversity of samples that would be required to complete the investigation.
• The physical condition of the samples (rock, pulverized rock, etc.).
• The vulnerability of specific sample types to degradation effects during sample collection, encapsulation, and transport, as well as the impact of this degradation on individual investigations.
• The measurements required at the time of sample collection in order to select appropriate samples and place them in the necessary geologic context.
• The mobility necessary to obtain required samples.
• The packaging and handling priorities necessary to preserve the characteristics of interest in the samples.

The results of this analysis are presented in detail in Appendix II. Below, we summarize the consensus of the ND-SAG that was derived from this analysis.

IV. Scientific Objectives of MSR

IV-A. History, *current context of MSR's scientific objectives*

The 2003/2005 Mars Sample Return mission (which was cancelled in 2000, prior to launch) was the most recent effort that formulated scientific objectives for MSR. The way this mission chose to frame its scientific objectives is shown in Table 1. Since 2000, there have been numerous scientific advances that have greatly increased our understanding of the Red Planet. It is critical to take these into consideration in setting the new scientific objectives for MSR. In particular, it is important to incorporate actual or anticipated results from the following:

Recent and ongoing flight missions. Since the last MSR analysis in 2000, the Mars Global Surveyor (1999–2006),

TABLE 1. SCIENTIFIC OBJECTIVES, 2003/2005 MSR, 2009 MSL, AND 2013 EXOMARS (ORDER LISTED AS IN THE ORIGINALS)

MSR (2003/2005)	MSL (2009)	ExoMars (2013)
1 Further our understanding of the potential and possible biological history of Mars	1 Characterization of geologic features, contributing to deciphering geologic history and the processes that have modified rocks and regolith, including the role of water	1 To search for signs of past and present life on Mars
2 Search for indicators of past or present life on the martian surface	2 Determination of the mineralogy and chemical composition (including such an inventory of elements such as C, H, N, O, P, S, etc. known to be building blocks for life) of surface and near-surface materials	2 To characterize the water/geochemical distribution as a function of depth in the shallow subsurface
3 Improve our understanding of martian climatic evolution and planetary history	3 Determination of energy sources that could be used to sustain biological processes	3 To study the surface environment and identify hazards to future human missions
4 Improve our understanding of constraints on the amount and history of water on and within Mars	4 Characterization of organic compounds and potential biomarkers in representative regolith, rocks, and ices	4 To investigate the planet's subsurface and deep interior to better understand the evolution and habitability of Mars
5 Acquire data to identify areas of possible interest for future scientific exploration	5 Determination of the stable isotopic and noble gas composition of the present-day bulk atmosphere	
6 Determine the nature of local surface geologic processes from surface morphology and chemistry	6 Identification of potential biosignatures (chemical, textural, isotopic) in rocks and regolith	
7 Determine the spatial distribution and composition of minerals, rocks, and soils surrounding the landing sites	7 Characterization of the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons	
	8 Characterization of the local environment, including basic meteorology, the state and cycling of water and CO_2 and the near-surface distribution of hydrogen	

Sources of information: MSR: O'Neil and Cazaux (2000); MSL: http://mepag.jpl.nasa.gov/MSL_Science_Objectives.html (as of January 7, 2008); ExoMars: Vago and Kminek (2007).

Mars Odyssey (2002–present), Mars Exploration Rovers (2004–present), Mars Express (mapping from 2004–present), and the Mars Reconnaissance Orbiter (mapping from 2006–present) have made important discoveries. These investigations have greatly improved our understanding of Mars and have resulted in progressive refinement of key martian scientific objectives, as documented by the evolution of the MEPAG Goals Document (MEPAG, 2001, 2004, 2005, 2006).

Future (but pre-MSR) flight missions. Two major missions to the martian surface are scheduled during the next 6 years—the Mars Science Laboratory (MSL, scheduled for launch in 2009) and ExoMars (scheduled for launch in 2013). Both missions will analyze rock samples on the surface of Mars using *in situ* methods. It is therefore necessary to consider the scientific objectives of these missions when planning the objectives of the first MSR mission and to build upon their expected accomplishments. The scientific objectives of the MSL and ExoMars missions, as of 2007, are listed in Table 1.

Meteorite studies. More than 35 martian meteorites have been found in Antarctica and desert environments by meteorite recovery programs, including private and government-sponsored efforts. The number of recovered meteorites continually increases. As a consequence, MSR scientific objectives and sample selection strategy must respond to scientific advances derived from meteorite studies and also complement the existing meteorite collections.

IV-B. Possible scientific objectives for a next decade MSR

To translate the general statements about the possible value of MSR into specifics (Appendix II), the ND-SAG analyzed how returned samples might contribute to each of the scientific objectives and investigations described by MEPAG (2006). The investigations listed in MEPAG (2006) do not have equal science priority, nor do they benefit equally from returned sample analyses. By considering the most important potential uses of returned samples, the ND-SAG has formulated 11 relatively high-level scientific objectives for MSR. We note, however, that no single landing site could address all these objectives. Those objectives that any single MSR mission could achieve would reflect the capabilities of its architecture/hardware and the geologic terrain and local climate of the site. Even though all these objectives could not be achieved on the first MSR mission, it is ND-SAG's hope that by making this analysis as complete as possible, it will set the scene for future MSR missions beyond the first one.

Prioritization of the scientific objectives. The ND-SAG team considered the relative priority of the possible objectives listed below, using the following prioritization criteria:

(1) The investigation priority in the Goals Document (MEPAG, 2006). The analysis in Appendix II finds that returned samples could significantly advance 34 of the investigations identified by MEPAG (2006), and each of these investigations has been assigned a priority by MEPAG. The way in which these 34 investigations are consolidated into the 11 objective statements below is shown graphically in Appendix IV.

(2) The impact of MSR on investigation(s) associated with these objectives. For 13 of the 34 investigations, MSR would not only be expected to advance them more substantially than for the others; in some cases, MSR is essential (shown by the color coding in Appendix IV).

However, the achievable degree of progress toward these scientific questions would also depend on the choice of landing site (and the kinds of samples that are available to be collected there), the capability of the engineering system (*e.g.*, the number and quality of samples), the degree of complexity of the geologic process under study (and how many samples it might take to evaluate it), and other factors. For example, Objective 5 involves processes that are very complex, and a quantum jump in our understanding may be difficult with only a few samples. However, the objective is clearly important, and we should let it help guide the engineering. For these reasons, the ND-SAG team felt it appropriate to list the scientific objectives below in only 2 general priority groups: the first 5 are considered high priority, and the last 6 are considered medium priority. These priorities will clearly need to be reconsidered as the specifics of MSR are refined.

(1) Determine the chemical, mineralogical, and isotopic composition of the crustal reservoirs of carbon, nitrogen, sulfur, and other elements with which they have interacted and characterize carbon-, nitrogen-, and sulfur-bearing phases down to submicron spatial scales in order to document processes that could sustain habitable environments on Mars, both today and in the past.

Discussion. *A critical assessment of the habitability of past and present martian environments must determine how the elemental building blocks of life have interacted with crustal and atmospheric processes (Des Marais et al., 2003). On Earth, such interactions have determined the bioavailability of these elements, the potential sources of biochemical energy, and the chemistry of aqueous environments (e.g., Konhauser, 2007). Earth-based investigations of martian meteoritic minerals, textures, and chemical composition at the submicron scale have yielded discoveries of their igneous volatiles, impact-related alteration, carbonates, organic carbon, atmospheric composition, and the processes that shaped them. The search for extant life requires exploration of special regions (sites where life might be able to propagate) and thereby invokes stringent planetary protection protocols. These protocols are less stringent at sites other than special regions where the search for past life would target fossil biosignatures preserved in rocks. This objective is an extension of MSL Objectives 1 through 4 (Table 1), ExoMars Objectives 2 and 4 (Table 1), and MEPAG Objective I-A, which collectively address the habitability potential of martian environments.*

(2) Assess the evidence for prebiotic processes, past life, and extant life on Mars by characterizing the signatures of these phenomena in the form of structure/morphology, biominerals, organic molecular and isotopic compositions, and other evidence within their geologic contexts.

Discussion. *The MER mission demonstrated that habitable environments existed on Mars in the past and that their geologic*

deposits are accessible at the surface (Squyres and Knoll, 2005a, 2005b; Des Marais et al., 2007). The Mars Express Orbiter OMEGA IR spectrometer mapped aqueous minerals that formed during the Noachian (Bibring et al., 2005; Poulet et al., 2005). The upcoming MSL and ExoMars missions will be able to provide information about the habitability (past or present) of their specific landing sites at even greater detail. Although ExoMars is designed to search for traces of past and present life (it should also be able to detect prebiotic organic materials), experience with martian meteorites and, more especially, microfossil-containing rocks from early Earth, has shown that identifying traces of life reliably is extraordinarily difficult because (1) microfossils are often very small in size and (2) the quantities of organic carbon in the rocks that are identifiable as biogenic or abiogenic are often very low (Westall and Southam, 2006). The reliable identification of mineral and chemical biosignatures typically requires some particular combination of sophisticated high-resolution analytical microscopes, mass spectrometers, and other advanced instrumentation. The particular combination of instruments that are most appropriate and effective for a given sample is often determined by the initial analyses. Accordingly, sample measurements must be conducted on Earth because they require adaptability in the selection of advanced instrumentation. Note that the specifics of how this objective is pursued would be highly dependent on landing site selection. The search for extant life would require that the rover meet planetary protection requirements for visiting a "special region." The localities that are judged to be most prospective for evaluating prebiotic chemistry and fossil life might not be the most favorable for extant life. However, all returned samples would assuredly be evaluated for evidence of extant life, in part to fulfill planetary protection requirements, whether or not the samples were targeted for this purpose. This objective is an extension of MSL Objective 6 (Table 1), ExoMars Objective 1 (Table 1), and MEPAG Objectives I-A, I-B, and I-C, which address habitability, prebiotic chemistry, and biosignatures.

(3) Interpret the conditions of martian water-rock interactions through the study of their mineral products.

Discussion. *Both igneous and sedimentary rocks are susceptible to water-rock interactions that range from low-temperature weathering through hydrothermal interactions. These processes could operate from the surface to great depths within the martian crust. Rocks and minerals affected by such processes are significant repositories of volatile light elements in the martian crust, and they have also recorded evidence of climate and crustal processes, both past and present. The compositions and textures of rock and mineral assemblages frequently reveal the water-to-rock ratios, fluid compositions, and environmental conditions that created those assemblages [also discussed by MacPherson et al. (2001)]. A significant fraction of the key diagnostic information exists as rock textures, crystals, and compositional heterogeneities at submicrometer to nanometer spatial scales. Textural relationships between mineral phases could help to determine the order of processes that have affected the rocks. This is key to determining, for example, whether a rock is of primary aqueous origin or, alternatively, was affected by water at some later time in its history. Accordingly, state-of-the art Earth-based laboratories are required to read the record of water-rock interactions and infer their significance for the geologic and climatic history of Mars. This objective is an extension of the discoveries of MRO, MEX, and MER that there is an extensive history of ancient interaction between water and the martian crust. Understanding these interactions over a broad range of spatial scales is critical for interpreting the hydrologic record and records of thermal and chemical environments. This objective is an extension of MSL Objectives 1, 2, and 8 (Table 1), ExoMars Objectives 2 and 4 (Table 1), and MEPAG Objectives I-A, II-A, III-A, and IV-A.*

(4) Constrain the absolute ages of major martian crustal geologic processes, including sedimentation, diagenesis, volcanism/plutonism, regolith formation, hydrothermal alteration, weathering, and cratering.

Discussion. *Constraining the absolute ages of martian rock-forming processes is an essential part of understanding Mars as a system. There are 2 aspects to this objective. First, dating individual flow units with known crater densities would provide a calibration of martian cratering rates. This is critical for the interpretation of orbital data because crater chronology is the primary method for interpreting both relative and absolute ages of geologic units from orbit, and the method can be applied on a planetary scale. The scientific community has strongly advocated for the calibration of the crater chronology method since the inception of the Mars Exploration Program (MEPAG Investigation III-A-3). Second, we need to understand the timing of different geologic processes in the past as the planet has evolved in time and space. The suitability of the products of different geologic processes to the methods of radiometric geochronology depends on when the isotopic systems closed. Igneous rocks are by far the most useful [see summary in Borg and Drake (2005)]. Constraints on low-temperature processes, such as sedimentation, weathering, and diagenesis, could be obtained most easily and definitively by finding sites that show discernable field relationships with datable igneous materials. For example, by determining the ages of igneous rocks that are interbedded with sedimentary rocks, the interval of time when the sediments were deposited could be constrained. In addition, the ages of secondary alteration of martian meteorites have been measured with some success (Borg et al., 1999; Shih et al., 1998; 2002; Swindle et al., 2000). Accordingly, chemical precipitates formed during diagenesis, hydrothermal activity, and weathering may be datable with Ar-Ar, Rb-Sr and Sm-Nd chronometers. However, sophisticated Earth-based laboratories would be required so as to perform these difficult measurements precisely, with multiple chronometers to provide an internal cross-check and interpret the meanings of these ages. This objective is an extension of MSL Objective 1 (Table 1), ExoMars Objective 4 (Table 1), and MEPAG Objectives I-A, II-B, III-A, and III-B, and has long been considered a major objective of MSR (e.g., MacPherson et al., 2001; 2002).*

(5) Understand paleoenvironments and the history of near-surface water on Mars by characterizing the clastic and chemical components, depositional processes, and post-depositional histories of sedimentary sequences.

Discussion. *Experience with the Mars Exploration Rovers Spirit and Opportunity demonstrates that sedimentary rock sequences, which include a broad range of clastic and chemical constituents, are exposed and that sedimentary structures and bedding are preserved on the martian surface. Discoveries by MRO and Mars Express further demonstrate the great extent and geologic diversity of such deposits. Sedimentary rocks could retain*

high-resolution records of a planet's geologic history, and they could also preserve fossil biosignatures. As such, sedimentary sequences are among the targets being considered by MSL and ExoMars. Previous missions have also demonstrated that the sedimentologic and stratigraphic character of these sequences could be evaluated with great fidelity, comparable to that attained by similar studies on Earth (e.g., Squyres and Knoll, 2005a, 2005b; Squyres et al., 2007a, 2007b). The physical, chemical, and isotopic characteristics of such sequences would reveal the diversity of environmental conditions of the martian surface and subsurface before, during, and after deposition. But much of the key diagnostic information in these sequences occurs as textures, minerals, and patterns of chemical composition at the submicron scale. Future robotic missions might include microscopic imaging spectrometers to examine these features. However, definitive observations of such features probably would also require thin-section petrography, SEM, TEM, and other sophisticated instrumentation available only in state-of-the-art Earth-based laboratories. This objective is an extension of MSL Objectives 1, 2, and 8 (Table 1), ExoMars Objectives 2 and 4 (Table 1), and MEPAG Objectives I-A, II-A, III-A, and IV-A .

(6) Constrain the mechanism and timing of planetary accretion, differentiation, and the subsequent evolution of the martian crust, mantle, and core.

Discussion. Studies of martian meteorites have provided a fascinating glimpse into the fundamental processes and timescales of accretion (e.g., Wadhwa, 2001; Borg et al., 2003; Shearer et al., 2008; Symes et al., 2008) and subsequent evolution of the crust, mantle, and core (e.g., Treiman, 1990; Shearer et al., 2008). Martian meteorites also record a history of fluid alteration as shown by the presence of microscopic clay and carbonate phases (e.g., Gooding et al., 1991; McKay et al., 1996; Bridges et al., 2001). Although the trace-element and isotopic variability of the martian meteorite suite far exceeds that observed in equivalent suites of basalts from Earth and the Moon (Borg et al., 2003), the apparent diversity of igneous rocks identified by both orbital and surface missions far exceeds that of the meteorite collection. This implies that an extensive record of the differentiation and evolution of Mars has been preserved in igneous lithologies that have not been sampled. Samples returned from well-documented martian terrains would provide a broader planetary context for the previous studies of martian meteorites and also lead to significant insights into fundamental crustal processes beyond those revealed by the martian meteorites. Key questions include the following: (1) When did the core, mantle, and crust first form? (2) What are the compositions of the martian core, mantle, and crust? (3) What additional processes have modified the crust, mantle, and core; and how have these reservoirs interacted through time? (4) What processes produced the most recent crust? (5) What is the evolutionary history of the martian core and magnetic field? (6) How compositionally diverse are mantle reservoirs? (6) What are the thermal histories of the martian crust and mantle, and how have they constrained convective processes? (7) What is the nature of fluid-based alteration processes in the martian crust? Coordinated studies of martian meteorites and selected martian samples involving detailed isotopic measurements in multiple isotopic systems, studies of microscopic textural features (melt inclusions, shock effects), and comparative petrology and geochemistry are needed to answer these questions definitively. These data would provide the basis for model ages of differentiation that are placed in the context of Solar System evolution. They would also permit some of the compositional characteristics of crust, mantle, and core to be determined, which in turn would allow geologic interactions between these reservoirs to be evaluated and their thermal histories elucidated. The tremendous value of this approach has been validated by geochemical studies on the returned lunar samples that have been more informative than any other means in deciphering the geologic history of the Moon. This objective is an extension of MSL Objective 1 (Table 1), ExoMars Objective 4 (Table 1), and MEPAG Objectives I-A, II-A, III-A, and III-B and has long been considered a major objective of MSR (e.g., MacPherson et al., 2001, 2002).

(7) Determine how the martian regolith was formed and modified, and how and why it differs from place to place.

Discussion. The martian regolith preserves a record of crustal, atmospheric and fluid processes. Regolith investigations would determine and characterize the important ongoing processes that have shaped the martian crust and surface environment during its history. The martian crust is a combination of broken/disaggregated crustal rocks, impact-generated components (Schultz and Mustard, 2004), volcanic ash (Wilson and Head, 2007), oxidized compounds, ice, aeolian deposits, and meteorites. The Viking, Pathfinder, and MER landers have also revealed diverse mineral assemblages within regolith that include hematite nodules, salt-rich duricrusts, and silica-rich deposits (e.g., Ruff et al., 2007; Wänke et al., 2001) that show local fluid-based alteration. The regolith contains fragments of local bedrock as well as debris that were transported regionally or even globally. These materials would accordingly provide local, regional, and global contexts for geologic and geochemical studies of the returned samples. Martian surface materials have also recorded their exposure to cosmic-ray particles. Cosmic-ray exposure ages obtained at Apollo landing sites have helped to date lunar impact craters (e.g., Eugster, 2003). Regolith returned from Mars should provide similar information that could in turn be used to constrain the absolute ages of local martian terrains. An MSR objective would be to examine returned samples of regolith mineral assemblages in order to determine the abundances and movement of volatile-forming elements and any organic compounds in near-surface environments and to determine their crustal inventories. The abundance of ice in the regolith varies dramatically across the martian surface. At high latitudes, water ice attains abundances of tens of weight percent below the top few tens of cm. Inventories of water ice at near-equatorial latitudes are less understood, but ice might occur below the top few cm (Feldman et al., 2004). The regolith is assumed to harbor a large fraction of the martian CO_2 and H_2O inventories, but their abundance has not yet been accurately determined. This objective is an extension of MSL Objectives 1, 2, 3, 4, 6, 7, and 8 (Table 1), ExoMars Objectives 1, 2, and 3 (Table 1), and MEPAG Objectives I-A, I-B, I-C, II-B, III-A, and IV-A.

(8) Characterize the risks to future human explorers in the areas of biohazards, material toxicity, and dust/granular materials, and contribute to the assessment of potential *in situ* resources to aid in establishing a human presence on Mars.

Discussion. Returned samples could help to accomplish 4 tasks that are required to prepare for human exploration of Mars (see Appendix II). These tasks include: (1) Understanding the risks that

granular materials at the martian surface present to the landed hardware (Investigation IV-A-1A), (2) Determining the risk associated with replicating biohazards (i.e., biological agents, Investigation IV-A-1C), (3) Evaluating possible toxic effects of martian dust on humans (Investigation IV-A-2), and (4) Expanding knowledge of potential in situ *resources (Investigation IV-A-1D). The human exploration community has consistently advocated that these tasks are essential for understanding the hazards and planning the eventual human exploration of Mars at an acceptable level of risk (Davis, 1998; National Research Council, 2002; Jones et al., 2004). Regarding possible martian biohazards, analyses of robotically returned martian samples might be required before human missions could commence in order to quantify their medical basis and to address concerns related to planetary protection from both a forward- and back-contamination perspective (Warmflash et al., 2007). This objective is an extension of MSL Objective 7 (Table 1), ExoMars Objective 3 (Table 1), and MEPAG Objective IV-A.*

(9) For the present-day martian surface and accessible shallow subsurface environments, determine the preservation potential for the chemical signatures of extant life and prebiotic chemistry by evaluating the state of oxidation as a function of depth, permeability, and other factors.

Discussion. *The surface of Mars is oxidizing, but the composition and properties of the responsible oxidant(s) are unknown. Characterizing the reactivity of the near surface of Mars, including atmospheric* (e.g., *electrical discharges) and radiation processes as well as chemical processes with depth in the regolith and within weathered rocks, is critical with regard to investigating in greater detail the nature and abundance of any organic carbon on the surface of Mars. Understanding the oxidation chemistry and those processes that control its variations would aid in predicting subsurface habitability, if no organics are found on the surface, and also in understanding how such oxidants might participate in redox reactions that could provide energy for life. Potential measurements include the identification of species and concentrations of oxidants, characterization of the processes that form and destroy them, and characterization of concentrations and fluxes of redox-sensitive gases in the lower atmosphere. Measuring the redox states of natural materials is difficult and may require returned samples. This objective is an extension of MSL Objectives 1 and 8 (Table 1), ExoMars Objective 2 (Table 1), and MEPAG Objectives I-A, III-A, and IV-A.*

(10) Interpret the initial composition of the martian atmosphere, the rates and processes of atmospheric loss/gain over geologic time, and the rates and processes of atmospheric exchange with surface condensed species.

Discussion. *The modern chemistry of the martian atmosphere reflects the integration of 3 major processes, each of which is of major importance to understanding Mars: (1) The initial formation of the atmosphere, (2) The various processes that have resulted in additions or losses to the atmosphere over geologic time, and (3) The processes by which the atmosphere exchanges with various condensed phases in the upper crust* (e.g., *ice, hydrates, and carbonates). Many different factors have affected the chemistry of the martian atmosphere; however, if the abundance and isotopic com-*

position of its many chemical components could be measured with sufficient precision, definitive interpretations are possible. We have already gathered some information about martian volatiles from isotopic measurements by Viking and on martian meteorites (Owen et al., *1977; Bogard* et al., *2001). In addition, MSL will have the capability to measure some, but not all, of the gas species of interest with good precision. This leaves 2 planning scenarios: If for some reason MSL does not deliver its expected data on gas chemistry, this scientific objective would become quite important for MSR. However, even if MSL is perfectly successful, it will not be able to measure all the gas species of interest at the precision needed, so returning an atmospheric sample could still be an important scientific objective for MSR. This objective is an extension of MSL Objective 5 (Table 1) and MEPAG Objectives I-A, II-A, II-B, and III-A.*

(11) For martian climate-modulated polar deposits, determine their age, geochemistry, conditions of formation, and evolution through the detailed examination of the composition of water, CO_2, and dust constituents, and determine isotopic ratios and detailed stratigraphy of the upper layers of the surface.

Discussion. *The PLD represent a detailed record of recent martian climatic history. The composition of the topmost few meters of ice reflect the influence of meteorology, depositional episodes, and planetary orbital/axial modulation over the timescales of order 10^5 to 10^6 years (Milkovich and Head, 2005). This objective addresses the priorities of MEPAG Investigation II-B-5. Terrestrial ice cores have contributed fundamentally to interpreting Earth's climatic history. Similar measurements of martian ices could be expected to reveal critical information about that planet's climatic history and its surface/atmosphere interactions (Petit* et al., *1999; Hecht* et al., *2006). The ability of ice to preserve organic compounds (and, potentially, organic biosignatures) may help address objectives associated with habitability and prebiotic chemistry and life (MEPAG Goal 1; Christner* et al., *2001). By exploring lateral and vertical stratigraphy of active ice layers and facilitating state-of-the-art analyses of returned materials, a rover-equipped sample return mission would significantly improve our understanding beyond what the Phoenix stationary lander is expected to achieve at its single high-latitude site. This objective is an extension of MEPAG Objectives I-A, II-A, II-B, and III-A.*

V. Samples Required to Achieve the Scientific Objectives

The MSR scientific objectives imply the return of several types of martian samples. These types arise from the variety of significant processes (*e.g.,* igneous, sedimentary, hydrothermal, aqueous alteration, etc.) that played key roles in the formation of the martian crust and atmosphere. Each process creates varieties of materials that differ in their composition, location, etc., and that collectively could be used to interpret that process. Accordingly, we define a "sample suite" as the set of samples required to determine the key process(es) that formed them. On Earth, suites typically consist of a few to hundreds of samples, depending on the nature, scale, and detail of the process(es) being addressed. However, as discussed in a subsequent section, suites of about 5 to 8 samples are thought to represent a reasonable compromise between scientific needs and mission con-

straints. The characteristics of each type of sample suite are presented below.

V-A. Sedimentary materials rock suite

Sedimentary materials would be a primary sampling objective for MSR. Data from surface-roving and orbiting instruments indicate that lithified and unlithified sedimentary materials on Mars likely contain a complex mixture of chemical precipitates, volcaniclastic materials and impact glass, igneous rock fragments, and phyllosilicates (McLennan and Grotzinger, 2008). Chemical precipitates detected or expected in martian materials include sulfates, chlorides, silica, iron oxides, and, possibly, carbonates and borates (McLennan and Grotzinger, 2008). Sand- to silt-sized igneous rock fragments are likely to be the dominant type of siliciclastic sediment on Mars. Sediments rich in phyllosilicates are inferred to derive from basaltic to andesitic igneous rocks that have undergone weathering that led to the formation of clay minerals and oxides (Poulet *et al.*, 2005; Clark *et al.*, 2007). Products of weathering are moved by transporting agents such as wind, gravity, and water to sites of deposition and accumulation. Sedimentary materials accumulate by addition of new material on the top of the sediment column, which thereby permits historical reconstruction of conditions and events starting from the oldest at the bottom and continuing to the youngest at the top of a particular depositional sequence. However, pervasive impacts have "gardened" (stirred and disrupted) many such layered sedimentary deposits; therefore, undisturbed sequences must be sought. Although hydrothermal deposits and *in situ* low-temperature alteration products of igneous rocks are products of sediment-forming processes, they are presented in separate sections to emphasize their importance.

Chemical precipitates formed under aqueous conditions could be used to constrain the role of water in the martian surface environment (*e.g.*, Clark *et al.*, 2005; Tosca *et al.*, 2005). Precipitates could form within the water column and settle to the sediment surface, or they could crystallize directly on the sediment surface as a crust. Any investigation that involves habitability, evidence of past or present life, climate processes, or evolution of the martian atmosphere would be enabled by the acquisition of these rocks (Farmer and Des Marais, 1999). Some, but not all, chemical precipitates have interlocking crystalline textures with low permeability, which would potentially allow preservation of trapped labile constituents such as organic compounds and sulfides (*e.g.*, Hardie *et al.*, 1985). Thus, intact samples of chemical precipitates would be critical for unraveling the history of aqueous processes, including those that have influenced the cycling of carbon and sulfur.

Siliciclastic sedimentary materials are moved as solid particles and deposited when a transporting agent loses energy. Variation in grain size and textural structures at scales from millimeters to meters are important indicators of depositional processes and changing levels of energy in the environment (Grotzinger *et al.*, 2005). Secondary mineralization of sedimentary materials is likely to be minimal if pore spaces are filled with dry atmospheric gases but is likely to be substantial if pore spaces are filled with freshwater or brine (McLennan *et al.*, 2005). Sub-millimeter textures at grain boundaries are indicative of processes that have mod-

ified the sedimentary deposit. Thus, individual samples of siliciclastic sedimentary materials would provide insights into transporting agents, chemical reactions, availability of water in surface environments, and the presence of currents or waves. A series of samples through a sedimentary sequence would provide critical insight into rates and magnitudes of sedimentary processes. Certain deposits such as chemically precipitated sediments, varved sediments, ice, etc., could provide insights into climatic cycles. Siliciclastic sedimentary materials are central to investigations that involve past and present habitability and the evolution of the martian surface. Fine-grained siliciclastic materials rich in phyllosilicates are likely to have low permeability and thus increase the potential for preservation of co-deposited organic matter and sulfide minerals (Potter *et al.*, 2005). Like chemical precipitates, samples of phyllosilicates that were deposited in aqueous environments would be critical for unraveling the carbon and sulfur cycle on Mars.

V-B. Hydrothermal rock suite

Hydrothermal deposits are relevant to the search for traces of life on Mars for several reasons (Farmer, 1998). On Earth, such environments can sustain high rates of biological productivity (Lutz *et al.*, 1994). The microbial life-forms that inhabit these environments benefit from various thermodynamically favorable redox reactions, such as those that involve hot water and mineral surfaces. These conditions can also facilitate the abiotic synthesis of organics from CO_2 or carbonic acid (McCollom and Shock, 1996). The kinds of molecules that are thus synthesized include monomeric constituents used in the fabrication of cell membranes (Eigenbrode, 2007). Not only do microorganisms inhabiting hydrothermal systems have ready access to organics, they are also supplied with abundant chemical energy provided by the geochemical disequilibrium due to the mixing of hot hydrothermal fluids and cold water. These energy-producing reactions are highly favorable for the kinds of microorganisms that obtain their energy from redox reactions involving hydrogen or minerals containing sulfur or iron (Baross and Deming, 1995).

Another important aspect of the habitability of hydrothermal systems is the ready availability of nutrients. High-temperature aqueous reactions leach volcanic rocks and release silica, Al, Ca, Fe, Cu, Mn, Zn, and many other trace elements that are essential for microorganisms. Because hydrothermal fluids are rich in dissolved minerals, they create conditions favorable for the preservation of biosignatures, *i.e.*, traces of the life-forms that inhabit them. Although the organic components of mineralized microfossils can be oxidized at higher temperatures (>100°C), more recalcitrant organic materials (*e.g.*, cell envelopes and sheaths) can be trapped and preserved in mineral matrices at lower temperatures [<35°C; Cady and Farmer (1996), Farmer (1999)] and thus allow chemical and isotopic analysis of organic biosignatures. Minerals implicated in the fossilization of hydrothermal microorganisms include silica, calcium carbonate, and iron oxide.

Some of the earliest life-forms on Earth might have inhabited hydrothermal environments (Farmer, 2000). Hyperthermophiles occupy the lowest branches of the tree of life (Woese *et al.*, 1990). Indeed, hydrothermal vent environ-

ments, with their organic molecule-forming reactions, chemical disequilibria, and high nutrient concentrations, are considered as a possible location for the origin of life (Russell and Hall, 1996). Some would argue, however, that the position of hyperthermophiles at the base of the tree of life is an artifact caused by the fact that such environments would have represented protected habitats during the Late Heavy Bombardment period, when a large part of the world's ocean was probably volatilized (Sleep *et al.*, 1989). But the fact that hydrothermal environments could serve as protected habitats in hostile conditions is relevant to the early history of Mars.

Recently, it has been suggested that the suites of minerals found at the surface of Mars (including silica and sulfates) could be related to hydrothermal/fumarolic activity (*e.g.,* Bishop *et al.,* 2002; Squyres *et al.,* 2007a, 2007b; Yen *et al.*, 2007). Hydrothermal activity is to be expected because volcanic activity has occurred at the surface within the last couple of million years, which demonstrates that active heat sources still exist (Neukum *et al.,* 2004). In the event that life arose on Mars and flourished at the surface during the first 500 My of its history, the gradual deterioration in surface conditions would have confined life-forms beneath the surface, perhaps to be preserved in the cryosphere and elsewhere. Conceivably, life might have adapted to subsurface environments during the first 500 My and persisted there since then. The subsurface environment might have sustained only very low rates of productivity, but it is also the most stable environment and a potential haven for life during large impacts. Volcanic activity in the vicinity of the cryosphere would lead to active hydrothermal systems that, in some cases, might extend to the surface (Clifford, 1987).

The detection of hydrothermal activity on Mars is extremely significant since these environments could represent ideal habitats for microorganisms that obtain their carbon and energy from inorganic sources. They might host extant life as well as the fossilized traces of its ancestors. Returning intact samples of this lithology might be difficult for geologically recent material, which tends to be friable. It would, therefore, be very important to document the geologic context of such samples in case they do not survive the return trip whole.

Criteria for sample size, selection, and acquisition protocol would be the same as for the sedimentary suite. Examples of possible lithologies for the hydrothermal suite include samples from subsurface veins, fumarole deposits, surface spring deposits from vent areas to distal apron environments, as well as altered host rocks.

V-C. Low temperature altered rock suite

Low-temperature alteration processes occur at near-ambient conditions on the martian surface (typically less than about 20°C) and include, among other things, aqueous weathering (including certain forms of palagonitization) and a variety of oxidation processes. Spectral observations made by Viking and Pathfinder first inspired the notion that rock surfaces on Mars are coated with thin veneers of altered material. Crude depth profiling provided by the RAT experiment on the MER rovers revealed thin (mm scale) alteration rinds on most rock surfaces studied. The exact nature of the

alteration processes remains under discussion, but most investigators agree that low-temperature, relatively acidic aqueous conditions were involved (*e.g.,* Haskins *et al.,* 2005; Hurowitz *et al.,* 2006; Ming *et al.,* 2006).

Low-temperature processes also influence the regolith during and after its deposition. The sulfur-rich composition of regolith has long been attributed to low-temperature aqueous processes that yielded sulfate and other secondary minerals. This was confirmed when the MER rovers identified reactive magnesium and ferric sulfate minerals in the soils (Yen *et al.,* 2007). The Viking gas exchange and labeled release experiments also demonstrated that a reactive and oxidizing compound in the regolith was capable of breaking down many organic species. The nature and origin of this compound remains controversial, but various models call for low-temperature processes, such as photochemical alteration, impact crushing, or oxidizing acid interactions (Yen *et al.,* 2000; Hurowitz *et al.,* 2007).

Understanding the conditions under which low-temperature alteration processes proceed would provide important insight into the near-surface hydrological cycle, including fluid/rock ratios, fluid compositions (chemical and isotopic, as well as redox conditions), and the mass fluxes of volatile compounds (see also MacPherson *et al.,* 2001, 2002). It would be particularly important to analyze complete alteration profiles, whether on rock surfaces or within regolith columns, because they would also constrain the kinetics of these alteration reactions.

Representative, intact (or at least reconstructed) profiles on rock surfaces would be required to understand these alteration reactions. Recent experimental work has shown that parent rock compositions (mineralogy) are an important variable in understanding these processes (Tosca *et al.,* 2004; Golden *et al.,* 2005). Consequently, a diverse compositional suite would be highly desirable and would require sample-site characterization during sample selection. Alteration profiles on rock surfaces would most readily be acquired by coring. The scales of alteration profiles range from less than 1 mm to perhaps as much as 1 cm, so sample sizes of at least 2 cm would be needed. Because alteration profiles are likely to contain small amounts of sulfate and perhaps other reactive minerals, these samples would be susceptible to degradation during sampling and transport to Earth by processes such as dehydration and chemical reaction, which in turn could also affect their physical integrity. Accordingly, sample encapsulation is deemed critical.

V-D. Igneous rock suite

The igneous rocks on Mars are expected to be composed primarily of lavas and shallow intrusive rocks of basaltic composition (McSween *et al.,* 2003; Christensen *et al.,* 2005), along with volcanic ash deposits (*e.g.,* Wilson and Head, 2007). Although more- and less-evolved silicic and ultramafic magmatic rocks may potentially be present and would be of great interest, they have not yet been unambiguously identified on the surface. Igneous rocks would be central to investigations that reveal the geologic evolution of the martian surface and interior because their geochemical and isotopic compositions constrain both the composition of mantle source regions and the processes that affected magmas during their generation, ascent, and emplacement (see also

MacPherson *et al.*, 2001, 2002). Although spacecraft instrumentation could measure many major elements, Earth-based analyses of returned samples would be necessary to determine most trace element and isotopic abundances of rocks. Melting and crystallization experiments in terrestrial laboratories would be based on the compositions of igneous rocks. Trace siderophilic element abundances and isotopic compositions in igneous rocks could constrain the nature of the core and possibly its interaction with the mantle. Because magmas carried dissolved volatiles to the surface, these rocks would also be critical to understanding the inventories of degassed volatiles and the cycling of water and carbon.

Only igneous rocks could be reliably dated with absolute radiometric dating techniques; therefore, they would be critical for calibrating the martian stratigraphic timescale. Quantifying cratering rates would allow absolute ages of martian surfaces to be derived from crater densities (Hartmann and Neukum, 2001). Unaltered igneous rocks that are geographically linked to extensive terranes with known crater densities would be required. This linkage would likely be accomplished by comparing their geochemical/mineralogical characteristics with local bedrock and by characterizing regional units with orbital remote sensing.

A large proportion of rocks on the martian surface are likely to have experienced at least some low-temperature alteration (Wyatt *et al.*, 2004). Significantly weathered samples, however, would not satisfy the needs of these investigations and, rather, would be better suited to investigations that involve rock/water interactions. Consequently, the low-temperature alteration products associated with the weathering of the igneous rock suite are discussed separately.

To accommodate these investigations, a suite of igneous samples with as much chemical and textural diversity as possible would be required. Although some basaltic rocks may appear similar in terms of major element abundances and mineralogy, a suite collected over some geographic area would be likely to exhibit differences in trace element and isotopic compositions that would be highly informative. If different types of igneous rocks are present, (*e.g.*, ultramafic or silicic rocks), additional samples of these rocks should be collected, as they could constrain fractionation processes on Mars. It is important to note that many different scientific objectives could be met with the same samples. For example, radiometric dating of a lava flow that overlies a sedimentary sequence might constrain the cratering rate, the mechanisms and timing of planetary differentiation and evolution, and the period when sedimentation occurred. The igneous rock suite is relatively robust; therefore, most geologic objectives could be met with minimal temperature control and encapsulation procedures. However, interactions with fluids derived from dehydration of other samples, physical mixing, and the abrasion of rock chips during transport could all be detrimental to these investigations.

FINDING: **MSR would have its greatest value if the rock samples are organized into suites of samples that represent the diversity of the products of various planetary processes. Similarities and differences between samples in a suite can be as important as the absolute charac-**

terization of a single sample. Four primary suites of rock samples are called for:

- **Sedimentary**
- **Hydrothermal**
- **Low-temperate water/rock products (weathering)**
- **Igneous**

V-E. Regolith

The martian regolith reflects interactions between the crust and the atmosphere, the nature of rock fragments, dust and sand particles that have been moved over the surface, H_2O and CO_2 migration between ice and the atmosphere, and processes that involve fluids and sublimation. Understanding regolith chemistry and mineralogy is vital to determining the fates of any organic constituents. Some aspects of regolith studies necessarily overlap studies of the local rock petrology, geochemistry, and hydrothermal and low-temperature alteration processes. Although global-scale transport processes may have homogenized much of the fine-grained martian regolith components, as shown by the similarity of most Viking and Pathfinder soil compositions (*e.g.*, Carr, 2006), the MER rovers have demonstrated that the regolith also contains a diverse range of mineral assemblages, some of which originated locally. Other materials, such as volcanic ash (Wilson and Head, 2007) and impact glass (Schultz and Mustard, 2004), may have come from greater distances. Understanding the mechanisms by which these assemblages are produced is necessary to understanding the evolution of the martian surface and key fluid processes. The recent identification of a silica-rich component in a Gusev Crater soil deposit that perhaps formed though hydrothermal processes (Ruff *et al.*, 2007) and the presence of hematite spherules in the Opportunity soil (Squyres *et al.*, 2004) highlight the importance of regolith studies. The mm scale alteration rinds identified on rocks in the regolith in Gusev may have resulted from the reaction of S- and Cl-bearing species with minute amounts of liquid water (Haskins *et al.*, 2005). Studying the mineralogy of alteration rinds within regolith granules would give an insight into water and oxidation processes on Mars over long timescales (MacPherson *et al.*, 2001).

A returned regolith sample would likely be evaluated in the following way:

Size distribution studies of regolith particles may yield information about local vs. distal provenance, as they did for Apollo regolith samples (McKay *et al.*, 1974).

Studies of regolith minerals and their morphology (with the use of SEM, TEM, FTIR, and Raman spectroscopy techniques) and the chemistry of various lithologies within the regolith (scanning electron microscopy, transmission electron microcopy, and EMPA) could help to quantify the mobility of water, weathering processes, diagenesis, and chemical alteration in martian regolith, as has been done for martian meteorites (Gooding *et al.*, 1988; Velbel, 1988; Treiman *et al.*, 1993) and Antarctic dry valley soils (Gibson *et al.*, 1983; Wentworth *et al.*, 2005).

Through studies of major elements and water soluble cations (Na^+, K^+, Ca^{2+}) and anions (Cl^-, SO_4^{2-}, NO^{3-}), the relative extent and importance of the aeolian, salt-rich, seasonally active, and permanently frozen soil horizons could be determined and should be possible to evaluate for martian regolith as well.

We already know that martian impact glasses contain trapped atmospheric gases (Bogard and Johnson, 1983), and the regolith could be an ideal sample in which to find this component. Gas-release studies would be important to interpret the history and evolution of the martian atmosphere.

Finally, a regolith sample would be used for toxicity tests, including intratracheal, corneal, dermal, and ingestion studies.

The mixed and complex nature of regolith samples could lead to unexpected findings. For example, Bandfield *et al.* (2003) proposed that atmospheric dust on Mars contains a few percent carbonate. This is important because carbonate provides a record of atmosphere-water-crust interaction. However, carbonates have not yet been conclusively identified on the surface of Mars, which makes the search for carbonates within the dust from a regolith sample an important component for detailed mineralogical study. Microscopic examination of the regolith sample in terrestrial laboratories would enable micrometeorites to be identified from which meteorite fluxes could be estimated.

A regolith sample is also likely to retain some CO_2 and H_2O. These might occur as ice or mixed clathrates. If acquired samples could be refrigerated at $-10°C$ to $-20°C$, it might be possible to identify their various potential species. Determination of CO_2 and H_2O abundance and isotopic compositions would lead to a greater understanding of the global inventories and cycling between crust, atmosphere, and poles of these compounds. For example, accurate paleotemperatures of hydrothermal systems could be determined from measurements of $^{18}O/^{16}O$ isotopic fractionation during water-mineral isotopic exchange in hydrothermal assemblages (sampled across Mars or in meteorites) by way of the isotopic analyses of martian ice as the starting water-reservoir composition (Valley *et al.,* 1997; Bridges *et al.,* 2001). If a polar landing is not chosen, then the regolith sample would take on additional importance as a likely source of the ice.

It is important to note that, for a geologic unit with a high presumed degree of heterogeneity, like the martian regolith, many of the measurements of interest could (and should) be done *in situ*, and regolith studies should be an important target for both landed missions and MSR. The basic field relationships, including measuring physical properties and their variation vertically and laterally, would best be done in place. However, sample return would be the best way to identify the altered and partially altered materials, trace minerals (*e.g.*, carbonates), rare lithologies, etc. It is also important to note that our experience with the Spirit rover has shown us that we don't have a good way of knowing the magnitude of geochemical/geologic variability within this unit on a planetary scale and the number of samples necessary to characterize it. This objective should be thought of as one that would require more than just the first MSR mission.

FINDING: **The regolith is an important part of the martian geologic system. Understanding how it was formed and modified, how and why it varies from place to place, and the role it plays in the water and dust cycles would be an important component of sample return.**

V-F. Polar ice

Samples of polar ice would be necessary to constrain the present and past climatic conditions on Mars as well as elucidate cycling of water. The samples necessary to achieve these objectives could include discreet samples of surface ice from the PLD or a seasonal frost deposit. Short cores (~1 cm diameter × 30 cm length) from the PLD or subsurface ice deposit would also be desirable. A single sample could provide critical input on surface/atmosphere interactions. A short core might resolve climatic variability in the last few 100 Ka to 1 Ma (Milkovich and Head, 2005). Annual layers could be observed in core samples, and isotopic signatures ($\delta^{18}O$, D/H) are expected to define annual temperature variability, changes in water reservoir availability and exchange with the atmosphere, and short-term climate variations (Fisher, 2007). The composition of entrained non-ice dust materials (*e.g.*, aeolian, volcanic tephra, impact glass) would help determine the sources and relative proportions of dust that reach the poles. Changes in the amount of entrained non-ice dust with depth would help to constrain estimates of the modulation of large-scale dust events and their seasonal variability (Herkenhoff *et al.,* 2007). The desired sample localities include northern and southern residual ice deposits, northern and southern PLD, and mid-latitude and tropical glacial deposits (Head and Marchant, 2003; Head *et al.,* 2006; Shean *et al.,* 2005, 2007). Ideally, several core samples would be extracted over lateral distances of ~1 km to validate stratigraphic models based on orbital imagery. On the polar plateaus, the areas between scarps and troughs are wide and flat, and the north polar troughs have walls whose maximum slopes are ~10°. A traverse that acquires multiple discreet samples along trough slopes where stratigraphy is well exposed would afford extensive vertical sampling of climatic history (Carsey *et al.,* 2005). Trough slopes are well within the range of slopes that the MER rovers successfully traversed in Endurance and Victoria craters and the Columbia Hills.

FINDING: **A single ice sample could provide critical input on surface/atmosphere interactions. A carefully selected short core might resolve climate variability during the last few 10^5 to 10^6 years. Although ND-SAG recognizes that returning an ice sample on the first MSR is implausible, it is important to keep this sample type in mind for future MSRs.**

Either drilling or coring technologies would be required to sample the ice. The capability to acquire 30 cm cores is not expected to require significant technological development. Technologies for coring or small drills exist from MSL and have been proposed for Scout missions. Scooping or

drilling would be required to sample surface ice or ice buried under dry soil. These samples must be encapsulated and kept frozen; however, meltwater would still provide critical isotopic and compositional information. The division of cores into subsamples is expected to be similar to that for rock samples, but it must be conducted under controlled conditions. Stratigraphic analyses of the cores must be conducted before they are divided, and if subsamples are accurately catalogued, the core could be returned to Earth in sections.

V-G. Atmospheric gas

Scientific objectives related to investigating the geochemistry of martian atmospheric volatiles include determining the following:

- The composition, origin, and evolution of the martian atmosphere through time as well as the processes that have modified the atmosphere.
- The concentration of trace organic gases, such as methane and ethane, their variation in space and time, and their relationship to a possible martian biosphere.
- Transient photochemical gases, such as ozone, hydrogen peroxide, and others, and their relationship to the oxidation of the martian surface.

As discussed in Appendix II, the systematics of martian volatiles should be studied in 2 complementary ways: analysis of atmospheric gas and analysis of gas released by the thermal decomposition of rocks of various types and ages. Collected gas samples could be utilized to determine the stable isotopic abundances, including noble gases and trace gas composition of the present-day bulk atmosphere (Appendix II, II-B-1). Likewise, the thermal decrepitation studies of solid samples could help to determine the history of the composition of the atmosphere (Appendix II, II-B-3). However, ND-SAG has concluded that determining the production/loss, reaction rates, and global 3-dimensional distributions of key photochemically reactive species is not easily possible by way of sample return because the species of interest are present in trace quantities and degrade relatively rapidly. The gas placed in the container on Mars would not be the same as the gas received in the lab on Earth. Characterizing organic gases to interpret possible biologic implications, though important to Goal I (Appendix II; *e.g.,* I-A-4, I-B-1, I-B-3), may also encounter similar difficulties in sample preservation. Thus, for the remainder of this section, the scientific objectives are considered in the context of the major inorganic gases, including the noble gases.

Our present knowledge of the martian volatile system comes from previous measurements by the 1976 Viking landers and from analysis of gases trapped in martian meteorites. Those results show that some atmospheric species (*e.g.,* N, H, Ar, Xe) have been isotopically fractionated by atmospheric loss into space. Models of both continuous loss and early episodic loss have been advanced (*e.g.,* Pepin, 1991), but the details of volatile loss remain largely unanswered. Atmospheric loss also has occurred on other terrestrial planets, such as Earth. To understand the specific atmospheric loss mechanisms, it is important to know the initial isotopic compositions of these gas species. Such knowledge may also indicate to what degree these volatiles were acquired during the accretion of Mars and later degassed from the interior, versus to what degree volatiles were added after accretion by, for example, comet impacts.

Knowledge about initial isotopic compositions mainly derives from analyses of volatiles trapped in solid samples, either in ancient rocks that contain volatiles accreted with Mars, or in condensed phases such as carbonates and hydrates, which represent major inventories of these volatiles on Mars. Earlier atmospheric gases also could be trapped in impact melts. The potential exists to use gaseous isotopes formed over time through radioactive decay (*e.g.,* ^{40}Ar, ^{129}Xe) and measured in samples of different ages to characterize early martian differentiation and evolution of the atmospheric inventory. Ancient volatiles trapped in martian meteorites give hints of initial volatile compositions, but some initial isotopic compositions (*e.g.,* D/H, ^{13}C/^{12}C, light noble gases) are largely unknown, as are details of variations in isotopic compositions through martian history, generated by volcanic degassing, loss to space, climatic cycles, etc. The ^{13}C/^{12}C, ^{18}O/^{16}O, and D/H isotopic ratios of atmospheric gases are important parameters in understanding chemical equilibria among atmospheric and condensed volatile phases, but these ratios are poorly known. Further, measurements of various volatiles in solid samples (igneous and sedimentary rock, chemical precipitates, impact glass, etc.) could elucidate the important volatile-containing phases within Mars and possibly variations in these phases across martian history and climatic cycles. An understanding of the C, O, and S isotopic compositions in condensed martian phases could be important in determining formation temperature and distinguishing biotic from abiotic chemical reactions that produced such phases (*e.g.,* Valley *et al.*, 1997; Farquhar *et al.*, 2000).

Comparisons of isotopic compositions of volatile elements like C, O, H, and S in various chemical forms and in different phases of returned samples could give a potential wealth of geochemical information about atmospheric and volatile interactions and evolution. The isotopic compositions of such species are subtly changed when they undergo chemical reactions or phase changes, and these isotopic differences may elucidate these phases and processes, and the temperatures involved. For example, the isotopic composition of carbon differs in predictable ways in carbonates precipitated from carbonate-bearing groundwater and in equilibrium with atmospheric CO_2. Further, such data could provide information about genetic relationships among sulfur- and oxygen-bearing phases, the oxidation pathways for compounds in the regolith that involve atmospheric species with anomalous oxygen isotope compositions (which could be affected by oxygen sinks), and the sources and mixing of martian sulfate. Although the isotopic compositions of these elements in the present and ancient martian atmosphere are important for such considerations, their atmospheric compositions are poorly known. Solid samples also are certain to contain noble gases produced by cosmic-ray bombardment of the martian surface, and these have likely altered the atmospheric noble gas composition over time.

In addition to what we know from Viking and study of the martian meteorites, MSL will carry an instrument (SAM) that is capable of measuring many components of the martian atmosphere, including the isotopic ratios of Ar, N_2, CO_2 (both C and O), Kr, Ne, Xe, the concentration of methane and

sulfur gases, and the D/H ratio in H_2O. The precisions and detection limits of SAM's capability in these areas is summarized in Table 2 (Appendix V; data from Mahaffy, written communication, 2008).

ND-SAG concludes that analysis of a returned martian atmospheric sample for Ne, Kr, CO_2, and CH_4 and C_2H_6 would confer major scientific benefit (Table 2). Characterizing the initial Kr component in the primitive atmosphere would require analytic precision beyond MSL's capabilities. Understanding processes of exchange between CO_2, CH_4, and exchangeable crustal reservoirs of carbon, oxygen and hydrogen requires highly precise stable isotopic measurements. A returned Xe sample would provide an improved estimate of the initial atmospheric Xe component and of minor components that have been added. However, returned samples of Ar, N_2, S gases, and H_2O would confer minimal benefits relative to what we expect to learn from MSL. The abundance and isotopic measurements of Ar and N2 achievable by MSL *in situ* would be sufficient to address the key open scientific questions in those areas. The S gases and H_2O have such low abundances and high reactivity that they would not be expected to survive the return to Earth in unmodified form. Appendix V explains the rationale for these findings in greater detail.

> FINDING: **A precise, multi-component analysis of a returned martian gas sample would make a major contribution to understanding the origin, evolution, and current state of Mars, even given the expected accomplishments by MSL in this area.**

V-H. Dust

Dust is the pigment of Mars in that it supplies the reddish hue to the Red Planet. Thick accumulations of dust are a significant component of the martian surface. The globally extensive high albedo, low thermal inertia regions of Mars may contain a meter or more of dust (Christensen, 1986). Intermediate albedo regions like those visited by 4 of the 5 landed missions show a patchy dust cover that is several cm thick in places. Even the low albedo surface of Meridiani Planum includes isolated occurrences of dust in the lee of obstacles as well as mixed into the regolith (Yen *et al.*, 2005). This dust is carried aloft during seasons of atmospheric turbulence, encircling the globe and then falling out over time onto all exposed surfaces both natural and human-made. Despite the ubiquity of dust and the multitude of orbital and surface analyses applied to it, some of the details of its mineralogy and chemistry remain elusive. Without these details, an important window into the weathering and alteration history of Mars remains closed (see also MacPherson *et al.*, 2001, 2002), and questions about its potential hazard to human explorers are left unanswered.

Beginning with telescopic observations, the bright regions of Mars were recognized as rich in oxidized iron. Visible / Near Infrared (VNIR) spectra are reasonably well matched by certain palagonitic tephras from Hawaii (Singer, 1982), which are described as hydrated amorphous silicate materials that contain nanophase ferric oxide particles. The role of water in altering the dust and its parent material has been recognized in subsequent years with orbiter observations of spectral features attributable to a water-bearing phase(s) (*e.g.*, Murchie *et al.*, 1993), including the possibility of zeolite (Ruff, 2004). Thermal infrared spectra provide evidence that a few weight percent of carbonate minerals may be present in the dust (Bandfield *et al.*, 2003). Measurements by the MER rovers clearly show that sulfur is enriched in the dust (Yen *et al.*, 2005) and that virtually all dust particles, which very likely are agglomerates, contain a magnetic phase (Bertelsen *et al.*, 2004) that probably is magnetite (Goetz *et al.*, 2005). Although martian dust shows evidence for aqueous alteration, the presence of olivine demonstrates that water did not play a dominant role in its formation (Goetz *et al.*, 2005).

V-I. Depth-resolved suite

Several of the life-related MSR objectives assign high priority to returning samples that contain reduced carbon. Because the surface of Mars is oxidized, organic matter might exist only at depth. Even if MSR is unable to acquire organic-bearing samples, it is important to acquire data in order to model the preservation potential of reduced species and, thereby, determine where organic matter might be accessible. The organic carbon measurements of the Viking landers indicate clearly that the surface (regolith) of Mars is oxidized to such an extent that any volatile organic components are being continuously destroyed. Although organic carbon compounds are raining down continuously from carbonaceous chondrites, cometary material, interplanetary dust particles, and micrometeorites (Flynn and McKay, 1990), the Viking experiments found no trace of them (Klein, 1978, 1979). It is hypothesized that prebiotic compounds that are relatively nonvolatile have been destroyed. Although there is indication that reduced organic compounds survive in the parent lithologies of martian meteorites (Steele *et al.*, 2007 and references therein), chemical modeling suggests that the depth of the oxidized surface layer is of the order of cm to several m (Dartnell *et al.*, 2007). Various oxidizing agents have been proposed, including OH, HO_2, and H_2O_2 species produced by photolysis of atmospheric water vapor (Zent and McKay, 1994; Zent *et al.*, 2003). These species could form complexes with metals in the martian regolith to create peroxy radicals. Another source of oxidation could be UV-silicate interactions that trap oxygen, which results in highly oxidized dust and soil particles, or perhaps even unknown "super-oxidants."

Models indicate that impact "gardening" of the regolith could mix the oxidant(s) to depths of a few meters (Zent, 1998). Kminek and Bada (2006) concluded that, over geologic timescales, ionizing radiation destroys organic matter (specifically, amino acids) to depths of at least 1.5 to possibly 2 m, though Dartnell *et al.* (2007) have shown that this effect is intrinsically linked to the amount of shielding of organic materials. With use of permeability-based modeling, investigators have estimated that oxidants penetrate to depths between 10 cm and 5 m in the regolith, depending on the model, time of exposure, and the nature of the regolith material (Bullock *et al.*, 1994). Thus, it might be desirable to obtain samples from as deep as 3 m into the regolith. Although it would be preferable to collect a set of samples from several depths, an alternative would be to collect a single larger sample from the maximum depth reached. Regarding bedrock and detached rocks,

TABLE 2. PLANNING ASPECTS RELATED TO A RETURNED GAS SAMPLE

Gas	Parameter of interest	Knowledge as of 2007		Precision expected from 2009 MSL (SAM instrument)	Analysis of returned sample				Mars Atm. required (cc at Mars P), 10 analyses
		Precision	Source		Precision	Magnitude of MSR benefit over MSL	Needed for one analysis (pico-moles)	Gas volume, STP	
Martian atmospheric gas chemistry									
Ar	$^{40}Ar/^{36}Ar$	~10%	Meteorites	2–10%	<1‰	MINIMAL	1	e-8 cc	0.001
	$^{38}Ar/^{36}Ar$	<5%	Meteorites	2–10%	<1‰	MINIMAL	1	e-8 cc	0.001
N₂	$^{15}N/^{14}N$	<5%	Meteorites	2–10%	<0.1‰	MINIMAL	10	e-7 cc	0.2
CO₂	Isotopes	5%	Viking	5–10%	<0.1‰	MAJOR	100	e-6 cc	1
Kr	Isotopes	<5%	Meteorites	2–10%	0.1‰	MAJOR	0.1	e-9 cc	5
Ne	Isotopes	~20%	Meteorites	Issues	<1‰	MAJOR	1	e-8 cc	10
Xe	Isotopes	<10‰ for all isotopes	Meteorites	2–10%	0.1‰	MODEST	0.1	e-9 cc	20
Methane	Abund.	TBD		<1 ppb	<0.1‰	MINIMAL			
	$^{13}C/^{12}C$	NONE		10%	1%	MAJOR?	e + 5		
	D/H	NONE		NONE	<1‰	MAJOR?	5*e + 4		
Ethane	Abund.	NONE		10's ppb		MAJOR?			
S gases	Abund.	NONE		10's ppb	<1‰	MINIMAL			
	Isotopes	NONE		Issues	<1‰	MINIMAL			
H₂O	D/H			2–5%	<1‰	MINIMAL	5000	e-4 cc	500
	$^{18}O/^{16}O$			NONE	<0.1‰	MINIMAL			

(1) More-abundant Xe and Kr isotopes are known more accurately, but the low-abundance isotopes, with the least accurate precision, are important in order to decipher the starting compositions.
(2) Caveat on the use of meteorites to interpret gas chemistry: assumes gas trapped in martian meteorites is the same as the current martian atmosphere.

the depth of oxidation presumably depends principally on time and the permeability and reactivity of the rock. Analyses of RAT holes during the MER mission indicate that Hesperian-age basalts have remained largely unoxidized within <1 cm of their surfaces (McSween *et al.*, 2006). Data from martian meteorites have shown that reduced carbon could be detected within carbonates from 3.6 Ga on Mars (Jull *et al.*, 1997; Flynn *et al.*, 1998; Steele *et al.*, 2007). Sedimentary bedrock at the MER Meridiani site has been oxidized to greater undetermined depths. A rock core at least several cm in length from an outcrop would allow for determination of the change with depth in composition (organic, inorganic, oxidation state) due to surface oxidation.

An important strategic consideration is that MSL (2009) and ExoMars (2013) will both collect data that will either increase or decrease the priority of the depth-resolved sample suite (see Fig. 1). MSL will carry a highly sensitive organic detection system (the SAM instrument) and obtain samples by drilling 5 cm into rocks and wheel-trenching up to tens of cm into regolith. ExoMars will also carry a very sensitive organic detection instrument (MOMA) and an oxidant detector (MOD). They will characterize gradients with depth in oxidation state, as well as the organic carbon, by way of so-called Vertical Surveys (VS), obtaining samples at 50 cm depth intervals from the surface down to 2 m. Two such VS acquisitions are planned for the nominal mission. If MSL discovers organic carbon at shallow depths in either rocks or regolith, the importance of a depth-resolved set of samples for MSR would decline. If MSL fails to detect organic carbon in shallow samples, but ExoMars detects it in deeper samples, the importance would increase substantially.

V-J. Other

Other types of samples would be of interest if encountered by an MSR sampling rover, but it would likely be hard to target the mission to acquire them. It is perhaps useful to think of them as samples of opportunity.

Impact products. Breccias might sample rock types that are otherwise not available in local outcrops and, thus, could be the most valuable. The utility of breccias in the Apollo collection has been demonstrated repeatedly (*e.g.*, James *et al.*, 1989). Impact excavation is the most plausible means of producing rock fragments on Mars, so it is possible that rocks from deeper levels in the crust might only be sampled in breccias. Diversity would be a major goal in collecting returned samples, and breccias often contain diverse materials. Impact melts would be highly significant for understanding the bombardment history. Testing the idea of a late heavy bombardment is particularly crucial and could be accomplished only by dating impact melts. Admittedly, these are not easy to identify, and all the basins are filled. There may be places, however, where craters have excavated below sedimentary or volcanic fill (*e.g.*, perhaps Hellas?).

Volcanic products. Volcanic tephra is also likely to be encountered as fine-grained components of the regolith or as layers and beds of tephra from nearby or faraway sources (*e.g.*, Wilson and Head, 1994, 2007). Such samples would supply important information on the mineralogy of explosive volcanic eruptions, grain-size information critical to the interpretation of volcanic eruptions and tephra transport, and ages of explosive eruptive phases of the history of Mars. Volcanic glasses would also represent a unique opportunity to sample primitive magmas from the mantle, as has been demonstrated on the Moon (*e.g.*, Delano, 1986).

Meteorites. Several iron meteorites have been found at both MER landing sites (Squyres *et al.*, 2006), and a few small cobbles in Meridiani have been suggested to be chondrites. If the residence time of a meteorite on the surface could be determined, the alteration histories of materials with well-known mineralogy, chemistry, and texture could give useful information about the rate of weathering (*e.g.*, Ashely *et al.*, 2007). It may be possible to do the same with a sample of fresh basalt that has been excavated to the surface. Obviously, allocating precious return mass to a meteorite would require a strong justification for the hypothesis being tested.

VI. Factors that Would Affect the Scientific Value of the Returned Samples

VI-A. Sample size

The mass of the individual samples and the total mass of the returned collection should be sized so as to provide enough material for (1) preliminary characterization, (2) life-detection (LD) and biohazard (BH) tests needed for planetary protection, (3) allocations to scientific investigations, and (4) representative reserves to be archived for future investigations. We need to plan for all future uses of sample material to determine the optimal sample size.

Preliminary examination. Preliminary examination is necessary to make decisions on what actions to take with each sample, including how each sample is subdivided. The samples from the Apollo, Antarctic Meteorite, Cosmic Dust, Stardust, and Genesis collections provide excellent precedents for planning this step for samples from Mars. Accordingly, the discussion here is based on nearly 30 years of experience gained from such activity at Johnson Space Center. As part of preliminary examination, techniques that are non-destructive or require minimal sample mass (*e.g.*, Ra-

FIG. 1. Importance of sampling to a depth of 2–3 m by MSR, given various potential scientific results from MSL and ExoMars.

TABLE 3. SUMMARY OF SAMPLE TYPES NEEDED TO ACHIEVE PROPOSED SCIENTIFIC OBJECTIVES

| | | | Main types of required samples | | | | | | | | |
| | | | Rocks | | | | | Other | | | |
Ref.	Goal	Objective nickname	Sedimentary suite	Hydrothermal suite	Low-T W/R suite	Igneous suite	Depth-resolved suite	Regolith	Dust	Ice	Atmospheric gas
1	I	Habitability	H	H	L	L	M	L		L	L
2	I	Prebiotic, life	H	H	L		M			M	L
3	III	Water/rock	H	H	H			M			
4	III	Geochronology	M	M		H					
5	III	Sedimentary record	H		M						
6	III	Planetary evolution				H		M			M
7	III	Regolith					M	H	M		
8	IV	Risks to human explorers					L	H	H	M	
9	I	Oxidation				H	H	M	M		
10	II	Gas chemistry	M	M		M					H
11	II	Polar							M	H	M

Priorities are expressed as relative High, Medium, and Low. Where there is no entry, the sample type would not make a meaningful contribution to the scientific objective.

man spectroscopy, XRF, FTIR spectroscopy, laser desorption-mass spectrometry, optical microscopy, scanning electron microscopy, electron microprobe analysis, time-of-flight secondary ion mass spectrometry) could be used to classify and characterize the samples (Table 5). The use of non-destructive techniques would maximize the quantity of sample available for subsequent investigations by the planetary scientific community. Preliminary determination of mineralogy would also be required, in part to place the biohazard tests in context (XRD, XRF, EDX, electron microprobe)—toxicity of the samples to biology requires a knowledge of the inorganic species present to ensure any toxic effects are linked to a biohazard (*e.g.*, presence of As, Cl, Br, etc.)

In addition, thin sections could be prepared and curated as is done for lunar and meteorite samples, with use of standard thin sectioning methods for small rocks and coarse fines. Focused ion-beam milling would be used to prepare small sections if necessary; this technique is being used for all kinds of samples from the lunar (Noble *et al.*, 2007), meteorite (Goldstein *et al.*, 2005), pre-solar grain (Stroud *et al.*, 2006), Stardust (Nakamura-Messenger *et al.*, 2007), and Mars (McKay *et al.*, 2006) communities. For very small samples, ultramicrotomy would be used to prepare thin slices that could be distributed to multiple scientists (Figure 12 in Zolensky *et al.*, 2008). Destructive techniques used during preliminary examination for sample preparation should be limited to those required to prepare the thin sections and slices by these 3 techniques.

Life-detection and biohazards testing. The most recent analysis of the test protocol for life-detection and biohazard testing for returned martian samples was published by Rummel *et al.* (2002; based on technical analysis done in 2000–2001). There have been significant improvements in analytic methodology since then, so the list of analytical methods and the required sample sizes must be updated substantially (for example, many techniques could be performed on a thin section, and the more extensive destructive techniques could be performed on sample splits on the order of 50–100 mg; dependent on the concentration of organic material (Elsila *et al.*, 2005; Glavin *et al.*, 2006). These tests would be grouped into 2 categories: (1) non-destructive (*e.g.*, Raman and confocal Raman spectroscopy, XRF, FTIR spectroscopy, laser-desorption mass spectrometry, and 3-D tomography) and destructive techniques designed to look for carbon compounds and their molecular structures (*e.g.*, with the use of a GC-MS, LC-MS, Py-GC-MS LAL, TOF-SIMS), and (2) nucleic acids via amplification techniques (*i.e.*, PCR—up to 1 gram of sample may be needed for this analysis). Since the volatile inventory is critical for assessing the presence of extant or extinct biomass, we would need some way to determine the abundance of the 4 light elements (C, H, N, and S) likely to co-occur in biosynthesized organic matter. In addition, the draft test protocol specifies plant and animal challenge tests, which would also be destructive.

The total amount of sample to carry out the life-detection and biohazard tests was estimated by Rummel *et al.* (2002) as 15–25 g, though this has sometimes been represented subsequently as ~10% of the returned sample. Given the near certainty that the total quantity of returned sample would be relatively small, it is important that only the amount absolutely needed be used for such purposes. We need to plan for the sample size and packaging that would be needed to carry out the hazard assessment protocol. A specific open issue is how to achieve statistically significant subsampling of the returned collection, particularly involving the rock samples.

There are 2 alternative strategies for allocating enough sample mass for these tests. Both strategies need further discussion by the community.

(1) Collect most of the incremental mass in the form of larger regolith samples (*e.g.*, one or more samples >30 g). Since the regolith is composed of components derived from multiple geologic sources, the regolith samples would contain a mixture of rocks, dust, volcanic ash, ejecta, decomposed bedrock, etc. Moreover, all of these have interacted with the martian atmosphere and obliquity-driven climate change. In short, they may represent an integration of martian surface geologic processes. This might be the best kind of sample in which to test for the possibility of forms that proliferate on the surface during intermittent warmer/wetter intervals and then become wind-blown constituents of the regolith. If there are significantly warmer periods during extreme obliquity, there may be the possibility of intermittent proliferation of a surface microbial community that is adapted to long periods of inactivity. Searching for spores or biopolymers (something equivalent to extracellular polymeric substances) could be a goal for regolith studies. If there is an extant microbial organism or community on Mars, it would need to be encased in desiccation-, oxidation-, and radiation-resistant molecules. This collection plan could allow for processing individual samples through the entire test protocol.

(2) Collect rock samples 1–2 g above what would be needed for scientific purposes, so that a split could be taken from each rock for destructive hazard-assessment testing. The hazard-assessment protocol consists of a package of tests, each of which would have different mass requirements. Thus, in this strategy it would be possible to run individual samples through some of the tests, but other more mass-intensive tests (*e.g.*, plant growth experiments?) may require the use of composite samples. As input for future, more-detailed discussion of this topic, ND-SAG offers that the rocks themselves could be the most probable habitat for martian life. The protective coating of the rock could help retain water, protect the interior from radiation, and reduce exposure of the endolithic (rock interior) habitat to surface oxidants. Thus, ND-SAG would be uncomfortable with a strategy that did not test for biohazards in at least some of the rocks.

Many of the non-destructive techniques could be performed on a thin section. Of the more extensive destructive techniques, sample splits on the order of 0.05–0.5 g would be needed per analysis, depending on the technique and sample composition. Given these mass estimates and allowing for multiple analyses of several different rock subsamples, an estimate of 2 g for these tests would be required. This estimate may be more or less dependent on the rock type, initial screenings, and changes in the analytical requirements as instrumentation advances. If less is used, that mass could be available for either the scientific investigations or future measurements (see ranges in Table 5).

FINDING: **ND-SAG recommends follow-up studies in 2 areas:**

- **Update the draft test protocol, incorporating recent advances in biohazard analytic methodology. Which**

tests need to be carried out on each sample, which could make use of composite samples, and what is the minimum quantity of sample material needed for each test?
- **Develop agreement on the criteria for taking a statistically significant subsample of the returned sample collection for the purpose of drawing conclusions related to the biosafety of the entire collection. What options for splitting individual samples are acceptable for this purpose?**

Research requests through principal investigators. To estimate the mass of rock sample that must be collected to meet analytical needs for various scientific investigations, we can turn to experience gained from the martian meteorite collection. In 1994, a 12.02 g meteorite, now referred to as QUE 94201, was found in the Queen Alexandra Range of the Transantarctic Mountains. This sample is a basaltic rock that also contains hydrous minerals (phosphate) and evaporites. Both of these mineral types could provide information about martian volatiles and igneous processes. Since 1994, this sample has been subdivided into 63 splits, including 27 bulk samples (4.416 g) for destructive analysis and 13 thin sections (using 2.2 g). To date, 23 principal investigators have studied the first set of splits (subsamples), and 29 principal investigators examined splits that were created subsequently. In addition, 5.16 g of material is still available for study with new techniques or by a new generation of scientists. Of relevance to any sample return mission is the attrition measured during sample processing; in the case of QUE 94201, 0.346 g (or ~3%) was lost during processing.

The manner in which QUE 94201 was subdivided and the number of investigators involved provide a relevant analog situation that might be expected for martian samples of similar size in a collected suite of rocks, such that a rock sample could be divided into subportions that are subsequently divided for various analyses. This would allow application of single analytical techniques on one portion of a sample or multiple analyses for techniques that have low mass requirements that may reveal spatial distributions. Also, an estimate of mass required for scientific investigations that use destructive techniques is provided by the QUE 94201 example: the average mass of QUE 94201 used for destructive analysis by individual PIs is 0.2 g (based on analysis in Table 1). Therefore, if 12–15 PIs are allocated material from an individual sample from a suite, that would require ~2.5 to 3.0 g. Notably, QUE 94201 was not tested for organic composition. Consequently, either additional sample mass would be necessary for organic tests for scientific investigations that extend beyond life-detection and biohazard screening by the SRF, or all the destructive tests applied would be limited to a select number of techniques determined based on the sample.

Sizing the rock samples. Adding up all the currently understood proposed uses of the returned martian samples, the minimum size for the purpose of the mission's scientific objectives would be about 8 g for both rock and regolith samples. If we assume that an additional 1–2 g of sample needs to be taken from each rock and regolith sample to support

Table 4. Subdivision History of Martian Meteorite QUE 94201

Type	Mass (g)	Techniques/notes	Information gained
(a) Destructive analysis	4.416	SEM, TEM, AMS, INAA, TIMS, stable isotope MS, noble gas MS, XANES, EMPA	Samples allocated to 23 PIs for studies of bulk composition (INAA), crystallization age (Lu-Hf, Rb-Sr, Sm-Nd, K-Ar, U-Pb), differentiation age (Hf-W, Sm-Nd), exposure ages (^{3}He, ^{21}Ne, ^{38}Ar, ^{81}Kr, ^{10}Be, ^{26}Al, ^{36}Cl, ^{14}C, ^{53}Mn), rock-atmosphere interactions (C, S, O, H isotopes)
(b) Thin-section production	2.2	SEM, TEM, SIMS, XANES, EMPA, optical microscopy	13 thin sections produced and studied by 29 different PI's from many scientific disciplines; first section allowed classification
(c) Non-destructive analysis	0.372	SEM, magnetic	Textural analysis, rock magnetization
(d) Still available for study	5.16	Includes mass from (c)	Sample material still being allocated 12 years later using new techniques and by next generation of planetary scientists
(e) Attrition	0.346	Material lost during processing	

biohazard testing, a good standard sample size would be 10 g each. Alternatively, if most of the biohazard testing is to be done on regolith samples, it may be possible to standardize on 8 g rock samples and 20 g regolith samples. A very similar conclusion (10–20 g samples) was reached, as seen in Appendix III, by MacPherson *et al.* (2005).

Occasionally, rocks and sediments exhibit fabrics and textures at the mm to cm scale that are highly diagnostic of their formation or subsequent alteration, or both. For example, the MER rover Opportunity documented the shapes and sizes of both grains and laminations that were consistent with the former presence of a shallow playa lake (Grotzinger *et al.*, 2005), and these features are of a scale that is best observed in larger samples. On Earth, other rock types (*e.g.*, igneous cumulates and high-grade metamorphic rocks) also locally exhibit large-scale textures that have high diagnostic value (*e.g.*, foliation, flow features, layering, segregations, etc.). Having the capability of collecting one or more samples of about 20 g may help to interpret such features correctly. This may be achievable from two 10 g samples collected adjacent to each other (*e.g.*, 1–2 cm apart). Alternatively, we may need to put a priority on documenting larger-scale textures *in situ*, so that the local context within heterogeneities larger than the sample size is documented.

Special note about the size of sedimentary rock samples. The minimal mass of samples of sedimentary deposits depends on the specific nature of the intended investigation. Experience from Earth suggests that sedimentological and stratigraphic studies normally need at least 5 g per sample

to have a sufficient area of bed surface and internal structure to observe and document orientation of stratification, sedimentary structures, grain-size distributions, grain contacts, and mineral composition. Although we don't know the concentration of organic molecules that might be present in returned martian samples, studies on terrestrial samples commonly involve 10–20 g per sample. Solvent-extractable organic compounds are present in many samples in low concentrations that approach instrumental detection limits. In such cases, 1–2 g of sample is needed per measurement; however, multiple analyses are commonly required to verify molecular structures. Careful documentation of geologic context is required for samples of sedimentary materials to relate their interpretation to the regional scale.

Sizing the regolith sample(s). The likely diversity of regolith materials, particularly at a geologically complex landing site, means that a number of separate regolith samples, *e.g.*, 3 each of 1–25 g, are preferred. A regolith sample of this mass is also likely to be appropriate for biohazard testing at the SRF. More-detailed information on sampling that involves trenching or drilling to depths on the order of tens of cm is given in Appendix II. For the purpose of MEPAG Investigation IV-A-5 (possible toxic effects of martian dust/regolith on humans), it is currently estimated that a minimum of 20 g may be necessary, though this kind of test could make use of composite samples.

Sizing the dust sample(s). Given the global homogeneity of dust on Mars (Christensen *et al.*, 2004; Yen *et al.*, 2005),

TABLE 5. GENERIC PLAN FOR MASS ALLOCATION OF INDIVIDUAL ROCK SAMPLES

Mass (g)	Goal	Specific purpose	Methods
EXAMPLE MASS ALLOCATIONS: ROCK SAMPLE			
Sample examination within SRF			
0.5	Get enough info. to make decisions about what to do with sample	Preliminary examination	Non-destructive or minimally destructive PE observations on thin sections; optical microscopy, SEM, EMPA
	LD-BH	Life-detection and biohazard non-destructive tests	Raman, confocal Raman, FTIR, XRF, LD-MS, 3-D tomography
2	LD-BH	Destructive tests associated with characterizing sample, including C chemistry	GC-MS, LC-MS, PCR, LAL, TOF-SIMS
Research requests from principal investigators			
1.0	Thin-section science	Develop at least 5 thin sections to support multiple investigations	SIMS, LA-ICP-MS, XANES, SEM, EMPA, FTIR, Raman
3.0	General research	Allocations within first year to 12–15 PIs for destructive and non-destructive investigations	Geochronology (TIMS, MC-ICP-MS), stable isotopes, Mössbauer, GCMS, LCMS
3.5	Future research	Stored for future analyses (beyond 1st year)	
10	**Total sample mass**		
EXAMPLE MASS ALLOCATIONS: REGOLITH SAMPLE			
Sample examination within SRF			
0.5	get enough info. to make decisions about what to do with sample	Preliminary examination	Non-destructive or minimally destructive PE observations on thin sections; optical microscopy, SEM electron microprobe
	LD-BH	Life-detection and biohazard non-destructive tests	Raman, confocal Raman, FTIR, XRF, LD-MS, 3-D tomography
2	LD-BH	Destructive tests associated with biohazard testing	GC-MS, LC-MS, PCR, LAL, TOF-SIMS, plant and animal tests
Research requests from principal investigators			
TBD	Thin sections on rocks sieved from regolith		Optical microscopy, SEM, EMPA, Raman, FTIR, SIMS, nano-SIMS, Mössbauer
TBD	Destructive geology-geochem investigations		Geochronology (SIMS), stable isotopes (SIMS), small particle studies (TEM, STEM)
TBD	Human toxicity tests		Estimate 20 g of sample needed, but composite sample ok
TBD	Future research	Stored for future analyses (beyond 1st year)	
15	**Total sample mass**		

a single sample from anywhere would likely be representative of the planet as a whole. However, because relatively pure dust deposits are often only mm thick, scooping a pure sample may be challenging in some locations. It is recommended that enough material be acquired to satisfy the needs of the various scientific investigations as well as to provide an amount of material sufficient to allow assessment of its potential hazard to humans and machines. As discussed in Appendix III, we need to plan for enough material for human toxicity studies to conduct intratracheal, corneal, dermal, and ingestion studies that would allow assessment of toxic effects. Past experience with lunar sample material and with lunar simulant has shown that 20 grams is likely to be sufficient, but these tests could be carried out with either dust or regolith. The fraction of interest for toxicity studies is in the <20 μm size fraction, and especially the <5 μm fraction.

Sizing the gas sample(s). Because of the wide range of concentration of the various gas species in the martian atmosphere, the quantity of atmospheric gas needed for measurement varies greatly among the different major species (Table 2). Also, higher analytic precision would be possible with larger samples, and multiple analyses of most species would be desirable. Consideration should also be given to possible gas sample contamination during return to Earth and distribution of subsamples of gas to various analytic labs. We suggest that a minimum returned gas sample should be 10 cm^3 at a pressure of 0.5 bar (since ambient martian atmospheric pressure is about 0.006 bar, this would require a compressed gas sample), which would provide enough gas material for a robust analytic program. If it is not possible to collect a pressurized martian gas sample, however, 10 determinations could be made with a 20 cc sample of gas at martian ambient pressure, and 4 high-priority measurements could be achieved (Table 2). Although this is lower-priority than a compressed sample, it would be well worth doing. Finally, it should be possible to recover the headspace gas within the sample canister, though this gas would be significantly less useful for scientific purposes than a sample that has been isolated. For example, the headspace gas may be contaminated by welding by-products during the sealing of the canister.

Atmospheric species probably would occur in some form and in widely varying concentrations in nearly all returned solid samples, either as trapped volatiles or as condensed phases such as hydrates, carbonates, or sulfates. One important property of martian rocks is that several components are present, including primitive trapped gases and atmospheric components, and these must be resolved. This is important for atmospheric gases, as these may have been incorporated at different times (paleoatmospheres) and may provide samples of the evolving martian atmosphere. Therefore, the precision of the measurements must permit these components to be resolved. Unfortunately, their concentrations are typically much lower in rocks from Mars, compared to those from Earth. For example, in nakhlite NWA998, the observed gas release is typically 0.2 ppm of N per temperature step, which gives an uncertainty of $\sim$0.5‰ from zero to $+150$ (Mathew and Marti, 2005). The release of xenon (^{132}Xe 0.1 to 5 e^{-12} cm^3/g) gave (one sigma) precision of 1% for rare isotopes (^{124}Xe, ^{126}Xe) and <5‰ for the abundant isotopes (*e.g.*, ^{131}Xe). When highly variable anomalies due to radi-

ogenic (^{129}Xe), fission (*e.g.*, ^{136}Xe) and spallation components (*e.g.*, ^{126}Xe) are observed, the uncertainties increase. ND-SAG concludes from all this that it is not feasible to set the minimum sample size of the rock samples based on their proposed use in gas-release experiments—we simply don't have enough information to know how to set the thresholds.

A final note. As Deep Impact has demonstrated, a small amount of material may make it possible to make a "preliminary investigation," and we should not underestimate what could be accomplished with samples smaller than ideal.

FINDINGS:

- **A full program of scientific investigations (12–15 PI allocations, multiple thin sections, wide diversity of applied instrumentation, preservation of 50% for future researchers) is expected to require samples of rock and regolith at least 8 g in size. However, for study of some kinds of heterogeneities, there may be value in one or more larger samples of $\sim$20 g.**
- **To support the sample mass required for biohazard testing, either some of the samples need to be larger (*e.g.*, 30 g), or each sample should be increased by about 2 g (endorsed) leading to an optimal sample size of about 10 g.**
- **Because of the importance of the trace atmospheric species, it would be scientifically valuable to have a gas sample that is both compressed (to get more mass), and isolated from rock and mineral samples.**

VI-B. Number of Samples

Natural materials are heterogeneous at scales ranging from atomic to planetary. Mineralogical, geochemical, biogeochemical, and morphological properties would be assumed to vary among samples, depending on the temporal and spatial distribution of processes active on Mars. In many studies, characterization of heterogeneities could provide as much information about processes as the specific characteristics of a given sample. Thus, for maximum scientific benefit, Mars sample-return missions would need to capture as much of this diversity as reasonable through careful selection of both landing sites and samples from each site. The number of samples needed to capture appropriate heterogeneity depends on the local martian environment and geologic history. Field experience on Earth has taught us the importance of acquiring sufficiently diverse samples to evaluate whether a specific result is representative as well as to extrapolate interpretations of processes from variations among and within samples. In many cases, carefully selected suites of related rocks allow for reasonable evaluation of (1) how representative each sample may or may not be of the geologic unit, (2) the consistency of processes creating and altering the samples, and (3) abundances of specific attributes such as minerals and geochemical signatures.

Without pre-characterization of a specific martian site, it is not possible to define the number of samples required to capture local-to-regional diversity in geologic materials. How-

ever, an estimate of sample number is necessary for mission planning. For many studies, a suite that consists of about 5 to 8 samples would be sufficient for a first-order evaluation of the heterogeneity of units, the consistency of processes, and the abundances of representative features. Two examples demonstrate this. In Endurance Crater, Mars, the analysis of 7 stratigraphically distributed sites in the Burns Formation allowed the Opportunity rover team to identify several significant diagenetic events, some of which were associated with variations in groundwater (McLennan *et al.*, 2005). In a second example, APXS analyses of 8 separate samples of alkaline volcanics revealed that they were formed under different conditions or from a very different starting composition compared to the bulk of martian rocks, which has offered new insight into the complexity of the martian interior (McSween *et al.*, 2006). In both of these examples, a smaller number of the "right" samples could have provided sufficient information for the resulting interpretations, but pre-selection of the smaller set of samples would have required significant characterization. Thus, for Mars sample return, extensive *in situ* characterization capabilities would be needed or a suite of at least 5 to 8 samples should be collected from each geologic unit. More samples would provide better information, but a suite of 5 to 8 samples should provide sufficient diversity to provide substantial scientific return.

Quantity of samples to be cached by MSL

The MSL cache is designed to accept rock samples 0.5–1.5 cm in size, as would be provided by MSL's soil scoop and collected over 5–10 separate caching events (Karcz *et al.*, 2007). The cache will have mesh sides to allow fines to filter out, leaving behind rocks. The strategy for employing the scoop to acquire either individual targeted rocks or rock-bearing regolith would depend on further experience with prototype scoops (note that the volume of the scoop is roughly half the volume of the cache). The empty cache is specified to have a mass less than 52 g. However, the mass of the latest revision of the design (as estimated by the CAD software) is 29 g (Karcz, written communication, 2008). A draft specification (as of this writing) is for the mass of the cache container when full to be 200 g or less. Because the mass of the contents will be uncertain, it is likely that the science team will fill it to somewhat less than capacity—to, say, 180 g instead of 200 g.

Table 6 shows a summary of some possibilities regarding sample number and overall mass. For the purpose of this table, both rock and regolith samples are assumed to be 10 g each (as per Table 5), and that encapsulation mass is assumed to be an additional 10 g per sample. In Case A (MSL cache would be recovered), the return of 20 rock, 3 regolith, 1 dust, and 2 gas samples, along with the MSL cache, would

TABLE 6. SUMMARY OF NUMBER, TYPE, AND MASS OF RETURNED SAMPLES

| Sample type | Mechanical properties | Number of samples | | Proposed science floor, 1st MSR | Returned mass | | | | |
		Min.	Pref.		Mass/ sample (gm)	Total sample mass	Vial mass/ sample (gm)	Total vial mass (gm)	Total mass (gm)
Case A. Cache from a previous mission is returned									
Sedimentary suite	Rock	5	15						400
Hydrothermal suite	Rock	5	10						0
Low-T W/R suite	Rock	5	10	20	10	200	10	200	0
Igneous suite	Rock	5	10						0
Other	Rock	1	2						0
Depth-resolved suite	Rock or reg.	5	10	0					
Regolith	Granular	1	5	3	15	45	15	45	90
Dust	Granular	1	1	1	5	5	5	5	10
Ice	Ice or liquid	5	10	0					0
Atmospheric gas	Gas	1	1	1	0.001		10	10	10
Cache from previous mission	Rocks	1	1	1	130	130	50	50	180
TOTAL				26		380		310	690
Case B. Cache from a previous mission is NOT returned									
Sedimentary suite	Rock	5	15						560
Hydrothermal suite	Rock	5	10						0
Low-T W/R suite	Rock	5	10	28	10	280	10	280	0
Igneous suite	Rock	5	10						0
Other	Rock	1	2						0
Depth-resolved suite	Rock or reg.	5	10	0					
Regolith	Granular	1	5	4	15	60	15	60	120
Dust	Granular	1	1	1	5	5	5	5	10
Ice	Ice or liquid	5	10	0					
Atmospheric gas	Gas	1	1	1	0.001		10	10	10
Cache from previous mission	Rocks	0	0			0	50	0	0
TOTAL				34		345		355	700

lead to a total returned mass of 690 g, of which 380 g would be samples. If 500 g is a firm limit for the total returned sample mass, the number of rock samples would have to be reduced to 12. In Case B (no MSL cache), the mass allocated for the cache could be used for additional rock and regolith samples of the same aggregate size. This could allow the number of rock samples to be raised to 28 and the number of regolith samples to 4; in this model, the total amount of sample mass would drop somewhat to 345 g.

Some implications and questions:

- Would a total mass of 700 g inside the returned container (instead of 500 g) break the mission?
- Because it might not be possible to determine whether the MSL cache is recoverable until MSR gets there (for example, MSL may end its life in an inaccessible location), it would be advantageous for MSR to carry enough sample vials for the full set of samples described in Case B of Table 6, not just those in Case A. That way, either scenario could be accommodated.
- The value of the MSL cache would need to be explicitly compared to an incremental 8 rock and 1 regolith sample having a known context and far better curation—these are mass equivalent. This comparison could be meaningfully made only after the cache has been loaded and the MSL science team knows its contents.

FINDING: **The minimum number of samples needed to address the scientific objectives of MSR is 26 (20 rock, 3 regolith, 1 dust, 2 gas), in the case of recovery of the MSL cache. These samples are expected to have a mass of about 350 g; and, with sample packaging, the total returned mass is expected to be about 700 g.**

VI-C. Sample encapsulation

For several reasons, the packaging of individual samples on Mars emerged as a central priority elucidated in this study, a conclusion also reached by MacPherson *et al.* (2005).

- *Avoid commingling of samples*. First, cross-contamination would likely occur without encapsulation, and it would degrade the scientific value of samples, particularly if samples from different sites are mixed. Mixing would be a particular problem for weakly lithified and friable samples that may break apart during transport to Earth.
- *Retain volatile components*. In addition, hydrous materials that are not maintained at Mars ambient conditions might dehydrate and form sulfur-bearing fluids that could readily react with other samples and the container.
- *Sample labeling for linkage to original field context*. Individual samples must retain their identities after they are returned to Earth. A friable sample would lose much of its identifying characteristics if it broke into multiple pieces during transport. It is imperative that the samples be linked to their collection sites even if the samples' physical and chemical integrity are altered during transport.
- *Maintain sample mechanical integrity*. Several investigations would require that the samples' macroscopic structures,

microscopic textures, and mineralogical spatial relationships be preserved during collection and transport. The samples' mechanical integrity must be preserved as well as possible. This is a particular concern for friable sedimentary rock samples that would be a major priority for MSR. Aqueous sediments could exhibit fabrics and textures at the mm to cm scale that are highly diagnostic of their formation or subsequent alteration, or both. For example, the MER rover Opportunity documented the shapes and sizes of both grains and laminations that were consistent with the former presence of a shallow playa lake (Grotzinger *et al.*, 2005). Much of the sulfate-rich bedrock at the Opportunity site appears to be weakly cemented and, therefore, seems prone to fragmentation that might destroy its valuable sedimentary textures.

The minimal sample encapsulation would be different for different investigations and rock types. Investigations related to organic chemistry, water, and other volatile components would require the most stringent encapsulation procedures to minimize any organic or biological cross contamination. These investigations would require hermetically sealed containers. In addition, rock samples that contain hydrous phases would require containers that would prevent fluids from escaping and reacting with other samples. The samples of granular materials (regolith and dust) obviously would require at least some form of mechanical packaging that would retain their identity as samples. Although it is a science priority that all samples be encapsulated, it would not be necessary for scientific purposes that they all have airtight seals.

Encapsulation is a particular issue for sedimentary rock samples. Some chemical and siliciclastic sediments are permeable or fragile and, therefore, could be highly susceptible to contamination and degradation during acquisition and transport. Many of these samples have the potential to break, disaggregate, dehydrate, and devolatilize. In addition, iron oxide and phyllosilicate materials, in particular, could adsorb volatile contaminants. Sample-to-sample contamination by water or organic compounds is a serious concern. Consequently, gas-tight encapsulation in inert containers is critical for samples of sedimentary materials.

An engineering trade to be evaluated would be whether a single airtight design should be used for all the samples or whether mass could be saved by having some vials that would be airtight and some that would be only "dust tight."

FINDINGS:

- **The scientific usefulness of the returned samples would depend critically on keeping them from commingling, on being able to uniquely identify them for linkage back to documented field context, and on keeping rock samples mechanically intact.**
- **Trading sample mass for packaging material is painful but necessary. A smaller number or mass of carefully managed samples would be far more valuable than a larger number or mass of poorly managed samples.**
- **The encapsulation for at least some of the samples must be airtight to retain volatile components.**

VI-D. Diversity of the returned collection

The diversity of the suites of returned samples must be commensurate with the diversity of rocks and regolith encountered during the mission. Sample suites that capture this diversity would empower the maximum possible number of investigations and, thereby, effectively address major questions, such as how geologic, climatic, and potential biologic processes have changed through time. The Viking landers and the Pathfinder and MER rovers have demonstrated that the martian surface is lithologically diverse. By returning samples to state-of-the-art terrestrial laboratories, more subtle mineralogical and compositional variations would be likely to emerge. Because the size of a sample suite reflects the number of samples necessary to characterize a given site, the set of suites that accurately represent the diversity of each key rock type at a site would constitute the minimum quantity of sample that would be required.

Changes in geologic, climatic, and potential biologic processes could only be addressed by examining multiple samples that represent different intervals of time. For example, to understand the origin and evolution of fluids responsible for sulfate deposition, numerous sulfate-bearing samples would be required that record evolution of any fluids through time. Likewise, understanding a siliciclastic depositional environment would require determining how the rock sequence changed through time; thus, a stratigraphic sequence must be sampled. Finally, understanding the evolution of the martian interior or an individual volcanic edifice would require sampling igneous rocks produced at different times. The lithologic diversity of the sample collection must be maximized to ensure that a record of any temporal mineralogical, geochemical, and organic chemical variations has been captured in the returned collection.

The lithologic, compositional, and temporal diversity of the returned sample collection may be the single most important factor controlling the range of investigations that could be addressed with the samples. For example, many investigations that involve habitability, the carbon cycle, the search for life, and the role of water on the martian surface would require rocks that contain hydrous phases. Some aspects of these investigations, as well as investigations regarding the evolution of the atmosphere, climate, surface, and interior of Mars, could only be addressed with siliciclastic sediments, igneous rocks, and regolith. Consequently, a primary exploration objective of MSR should be to maximize scientific yield by ensuring that the sample collection has the largest possible lithologic diversity. This essential objective should substantially influence both the selection of landing sites and the development of rover operation protocols. For example, mission strategies to acquire samples by visiting multiple sites are more effective at capturing a greater diversity of samples.

> **FINDING: A primary factor in the ultimate scientific value of MSR would be the diversity of the returned samples. The more diverse the collection, the more useful it would be in understanding the natural processes (past and present) on Mars.**

VI-E. In situ *measurements for sample selection and documentation of field context*

The scientific value of MSR would depend critically on the ability of the mission science team to select wisely the relatively few samples that could be returned, and on the degree to which the field context of these samples is known. To achieve these 2 functions, the MSR sample acquisition rover must be able to perform certain remote and *in situ* measurements.

ND-SAG has found that the instrument needs for MSR would be different in the 2 scenarios listed below:

- *Case A*. The MSR rover either goes to a previously unvisited landing site, or it gets "off the beaten track" of a previously visited site. In this case, both sample selection and documentation of context would need to be done.
- *Case B*. The MSR rover "follows in the footsteps" of a previous rover that has already established the field context and identified the exact materials to be sampled.

For Case A, 5 measurements are important to support the collection of samples that could be used for a wide range of scientific objectives: (1) High-quality color panoramic imaging would be essential to identify samples of interest and to determine their local geologic context (*e.g.*, Grotzinger *et al.*, 2005). (2) A microscopic imager that examines rock and sediment textures for clues about processes and environments of formation would also be essential. In addition, microbially induced textures are one of the key indicators of life (*e.g.*, Herkenhoff *et al.*, 2004). (3) The mineralogy would need to be determined to discriminate one rock from another and to establish geologic context of the samples (*e.g.*, Christensen *et al.*, 2004). Minerals reflect the processes and conditions associated with the formation of geologic materials. For example, understanding compositional variability in the igneous sample suite would require rocks that contain a range of minerals, such as olivine, pyroxene, feldspar, and oxides. Phyllosilicates, sulfates, carbonates, and silica-rich minerals are excellent for retaining evidence of aqueous processes and evidence of habitable environments and life. (4) Measurements of elemental abundance have been critically important during the MER mission (*e.g.*, Ming *et al.*, 2006; McSween *et al.*, 2006) and would be essential in understanding the range of variability within a field site and identifying the effects of unusual geologic processes. This information would be key to both sample selection and documentation of context. (5) Reduced-carbon measurements would be centrally important to understanding prebiotic chemistry, habitability, and life (*e.g.*, Schopf, 1983); therefore, reduced carbon should be measured during the sample selection process. Although we could certainly detect reduced carbon in returned samples to better than 1 ppb, ppm level sensitivity may be sufficient for screening for sample selection on Mars. The SAM instrument on MSL and the Urey and MOMA instruments on ExoMars will presumably give us important guidance on this after 2010. Finally, a rock abrasion tool would be essential to characterize the rocks adequately. Because many rocks on Mars have dusty or weathered surfaces, correct determination of the characteristics of the underlying rocks would require access to fresh surfaces.

For Case B, ND-SAG has concluded that the payload could be reduced to the following 2 instruments: color stereo im-

TABLE 7. ROVER-BASED MEASUREMENTS TO GUIDE SAMPLE SELECTION

What is needed	Suggested measurement	Case A	Case B
Ability to locate samples	Color stereo imagery	YES	YES
Ability to determine fine rock textures (grain size, crystal morphology), detailed context	Microscopic imagery	YES	YES
Ability to differentiate rock types, effects of different natural processes	Mineralogy	YES	NO
Ability to differentiate rock types, effects of different natural processes	Bulk elemental abundance	YES	NO
Ability to detect organic carbon	Organic carbon detection	YES	NO
Ability to remove weathered or dust-coated surface and see unweathered rock	Abrasion tool	YES	NO

Case A: MSR gets "off the beaten track." This assumes that a future MSR would go to either a fresh site or outside the area studied by a previous rover, where understanding the geologic context still needs to be done. Case B: MSR follows the tracks of a previous rover, which has documented the context.

agery and microscopic imagery. In this case, the MSR rover would not need to determine the geologic context and identify the materials to be collected—the prior mission would have achieved these tasks. However, ND-SAG also concludes that Case B has substantial risk, and it is not endorsed unless this is the only way the mission could be done. For a variety of reasons, it may not be possible for the MSR rover to follow the tracks of the previous rover. In addition, MSR would not have enough functionality to make excursions off the previous rover traverse, which may be desirable to follow up on unexpected results, including those from the previous mission. The Case B rover would have minimal analytical capabilities for an extended mission after the MAV leaves. Finally, if the MSR rover follows another rover that is neither as clean nor as sterile as the MSR rover, important implications arise that involve planetary protection and contamination control, and these should be evaluated further.

FINDINGS:

- **There is a difference in the minimum measurement capability of the MSR rover depending upon whether it would go to a previously visited site or to a fresh site.**
- **For a fully functional MSR rover, capable of interpreting geologic context on its own, 5 kinds of observations would be needed (macroscopic and microscopic imagery, mineralogy, elemental analysis, and organic carbon detection).**
- **If MSR is restricted to previously occupied sites and is dependent on prior information for sample-selection decisions, the number of instruments could be reduced to 2. However, restricting the retrieval of documented samples to previously visited sites would increase both scientific risk and planetary protection concerns.**

VI-F. Surface operations

To achieve the MSR scientific objectives and access the kinds of sites of greatest current interest, a high priority would be to deploy a spacecraft that has significant horizontal range and could navigate rough terrain. Although the current orbital imagery provides excellent context and mineralogical information for identification of high-priority landing sites, experience from the MER rovers has shown that the diversity of potential samples that exists at the size scale of a rover must be analyzed *in situ*. The MSR lander/rover must have instrumentation that could interpret the diversity of geologic materials and help to select the highest-priority samples for return (see Section VI-D). Color imagery, remote spectroscopic observations, and contact geochemical/mineralogical analyses constitute the minimum set of techniques that would be needed to optimize sample selection. The duration of surface operations would also influence the quality of the sample collection. ND-SAG expects that a minimum of 6–12 months of surface operation would be required to reconnoiter a site and identify, characterize, and collect a set of samples that captures its compositional diversity. To place this in context, the Opportunity rover did not complete the stratigraphic characterization in Endurance crater until sol 315 (Squyres and Knoll, 2005a, 2005b), and Spirit did not identify significant indicators of aqueous processes until it reached the Columbia Hills (roughly sol 180; Arvidson *et al.*, 2006). Sending MSR to a previously visited site (either of the 2 MER sites, the MSL or ExoMars site, or potential future sites) might substantially reduce the time needed for reconnaissance, but revisiting a site might also compromise samples intended for organic analyses by increasing the risk of terrestrial contamination.

FINDING: The collection of a diverse set of rock samples from known geologic context would require significant surface mobility. Also necessary is information about the diversity of surface materials (could be collected either by a prior mission or by the MSR rover) in order to select samples that span that variation. A minimum duration for surface operations of at least 6–12 months is anticipated, depending on landing site geography/geology and relationship to prior missions.

VI-G. Sample acquisition system priorities

To attain the full scientific value of rock samples, the sample acquisition system must be able to achieve the following:

- Sampling of both the weathered exterior and unweathered interior of rocks.
- The ability to sample a continuous stratigraphic sequence of outcrops (*e.g.*, the Burns Cliff at Meridiani Planum).
- In the case of rocks in outcrop with differential hardness, the ability to sample both less-resistant beds and more-resistant beds.
- The ability to relate the orientation of structures and textures in samples to those in outcrop surfaces, bedding planes, stratigraphic sequences, and regional-scale geologic structures.
- The ability to maintain the structural integrity of samples.

Given the sample sizes discussed in this report, these priorities would be best served with a small arm-mounted coring device [this sampling system was judged to be essential by MacPherson *et al.* (2005)]. An example geometry that would be of the right size is a small core of about 1 cm in diameter and 2–3 cm in length (how to optimize these parameters is still under discussion). To distinguish this from larger drills with depth capability of 2–3 m, we refer to it as a mini-corer.

The simplest way to sample granular materials, such as regolith and dust, might be with the use of a scoop. However, it may be possible to engineer a mini-corer so that it could also be used to sample granular materials.

FINDING: **The most important sample-collection tools for MSR would be a mini-corer and a scoop. Of lower priority, but valuable for specific kinds of samples, would be a gas compressor and a drill.**

VI-H. Temperature

The issues related to temperature sensitivity of martian minerals and organics were reviewed in great detail by MacPherson *et al.* (2005) (see Appendix III) and so are not repeated here. At that time, the scientific community expressed significant concerns about sample degradation at temperatures above 0°C; and, if anything, the scientific accomplishments of the Mars program over the past 3 years appear to have intensified those concerns (*e.g.*, Clark *et al.*, 2005; Bibring *et al.*, 2006; Peterson *et al.*, 2007). The perceived effects of temperature on achieving science goals are summarized in Table 9.

Certain chemical species that would have great scientific value for MSR are also sensitive to temperatures barely above those attained in the current martian environment. Examples include organic material as well as reactive minerals that might be common (*e.g.*, sulfates, chlorides, and clays), yet whose stability could be compromised even at modest temperatures (<20°C). Liquid water or ice also might be present in samples, either interstitially or sorbed onto mineral surfaces. Accordingly, the temperatures experienced by samples during collection and return to Earth would be a critical issue. To maintain sample integrity, returned samples ideally should be kept as close as possible to the ambient temperature (and atmospheric) conditions of the location where they were collected. However, the ND-SAG recognizes that, if this is set as a mission requirement, it might pose a major technological challenge that may not be achievable within cost constraints. If sample integrity is seriously affected by temperature excursions, then the next best option would be to monitor the temperature history closely and also ensure that samples are fully encapsulated so that all components would be retained. Under these conditions, any chemical reactions that may take place during transport to Earth conceivably could be evaluated and reconstructed.

Elevated temperatures could compromise the integrity of organic compounds [see MacPherson *et al.* (2005) for a good summary table]. Even at only −5°C, certain organic compounds are mobilized, and some organic compounds decompose at > −20°C. At temperatures of +50°C, significant decomposition takes place; and if samples remain at this temperature for more than about 3 hours, scientific objectives related to life goals could be seriously compromised.

Most inorganic materials should remain suitable for allowing primary scientific objectives to be achieved even if these materials experience temperatures as high as +20°C.

TABLE 8. SCIENCE PRIORITIES RELATED TO THE ACQUISITION SYSTEM FOR DIFFERENT SAMPLE TYPES

Sample type	Mechanical	Mini-corer	Big drill	Scoop	Tongs	Rake	Other
Sedimentary suite	Rock	H		L		L	
Hydrothermal suite	Rock	H		L		L	
Low-T W/R suite	Rock	H		M	M	M	
Igneous suite	Rock	H		L	L	M	
Depth-resolved suite	Rock or Reg.		H				
Regolith	Granular	H	H	H		H	
Dust	Granular			H			M
Ice	Ice or liquid						H
Atmospheric gas	Gas						H
Other	Rock	H		L	M	M	

H, High priority; M, Medium priority; L, Lower priority.

TABLE 9. EFFECT OF MAXIMUM SAMPLE TEMPERATURE ON THE ABILITY TO ACHIEVE THE CANDIDATE SCIENTIFIC OBJECTIVES

	Objectives achievable if max. temp. reaches:			
	50°C for 3 hours	20°C	−20°C	Notes
Sedimentary suite	Serious questions	Some	Most; desired	Assumes sampling to several cm; may want down to −50°C (TBR) if have hydrated sulfate minerals; need to distinguish non-sulfate materials
Hydrothermal suite	Most	Yes	Desired	These rocks may entomb the organics; if samples includes sulfates, lower temperature is critical
Low-T W/R suite	Some	Yes	Desired	Phyllosilicates or sulfates are viable candidates; need sulfate temperatures; lose S hydration states at 50°C
Igneous suite	Yes	Yes	Yes	
Depth-resolved suite				
Regolith	Some	Yes	Desired	
Dust	Some	Yes	Yes	
Ice	Serious questions	Serious questions	Yes	
Atmospheric gas	Yes	Yes	Yes	
Other	Yes	Yes	Yes	50°C fine for meteorites

At higher temperatures, such as +50°C, some materials (*e.g.*, regolith, dust, clays) might deteriorate and potentially lose key scientific information. Although the kinetics of many reactions is poorly known and some metastable phases may persist well outside their nominal stability ranges, sulfate minerals are very likely to present a special challenge. For example, the hydration states of magnesium and iron sulfates are sensitive to temperature and relative humidity, and changes (dehydration and/or melting) might commence at temperatures as low as −2°C. Dehydration and melting should be expected if temperatures reach 20°C. These changes have the potential to influence both the chemical and physical state of the samples. For example, dehydration of $MgSO_4 \cdot nH_2O$ from $n = 11$ to $n = 1$ would result in nearly a factor of 4 loss of mineral volume that could lead to physical disaggregation of weakly cemented samples. Release of water could result in further chemical reactions, such as dissolution of highly soluble minerals (*e.g.*, chlorides), leaching of weakly held ions (*e.g.*, clays), or significant lowering of pH through Fe^{3+} hydrolysis. Finally, water ice may be stable within cm of the Mars surface (*e.g.*, Mellon *et al.*, 2004); therefore, it could occur in a regolith sample or drill core. Refrigeration and temperature monitoring would allow an accurate assessment of whether any reaction between this water and the surrounding sulfates or soluble minerals has taken place during sample return.

The ND-SAG has confidence that the MSR scientific objectives that depend upon mineral compositions could be addressed if samples are kept below about −10°C. For preservation of water, it would be preferable to hold the samples below about −20°C (MEPAG SR-SAG, 2006). There is less confidence, but it is likely, that most objectives would be met for samples that are kept below about +20°C. If samples are allowed to reach +50°C for greater than about 3 hours, the damage that ensues would seriously degrade the scientific value of the samples. It is very possible that samples that contain Mg sulfates and Fe sulfates would be altered substantially even if temperatures approach only 20°C, but these

effects could be mitigated if samples are encapsulated and their temperature history monitored. Monitoring sample temperature during transport to Earth would help determine any post-sampling melting or recrystallization. For example, $MgSO_4$ of unknown hydration state was identified at the Opportunity site. This has been speculated to be $MgSO_4 \cdot 11H_2O$, which has subsequently been found on Earth (Peterson *et al.*, 2007) and is expected to dehydrate at 2°C. Maintaining a low temperature would inhibit this mineralogical transformation.

Far worse for the scientific value of the samples than heating to 20–50°C would be heating to a level sufficient for biological sterilization. It is a common misconception that heat sterilization of samples would damage them relative only to astrobiological (MEPAG Goal I) goals (*e.g.*, Steele *et al.*, 2007). Heat sterilization would impact the samples in several ways, some relevant to the other objectives of the mission.

> **FINDING: MSR's scientific objectives could most confidently be met if the samples are kept below −20°C and with less confidence if they are kept below +20°C. Significant damage, particularly to our life goals, would occur if the samples are allowed to reach +50°C for 3 hours. Temperature monitoring during the return mission would allow assessment of any changes to the samples.**

VI-1. Planning considerations involving the MSL/ExoMars caches

A decision was made in mid-2007 to add a simple caching capability to the 2009 MSL mission. As of this writing, a similar cache is under consideration for ExoMars. This capability is part of a larger strategy to utilize pre-MSR landed missions to enhance the value of sample return. It is intended that the recovery of the MSL cache would be an option for

MSR, rather than a requirement. The decision would be made several years from now by future science teams and other decision-makers.

The MSL cache design. The MSL cache is designed to accept 0.5–1.5 cm of rock samples provided by MSL's soil scoop, collected over 5–10 separate caching events (Karcz *et al.*, 2007). The cache will have mesh sides to allow fines to filter out, leaving behind rocks. The strategy for employing the scoop to acquire either individual targeted rocks or rock-bearing regolith would depend on further experience with prototype scoops (note that the volume of the scoop is roughly half the volume of the cache). The empty cache is specified to have a mass less than 52 g. However, the mass of the latest revision of the design (as estimated by CAD software) is 29 g (Karcz, written communication, 2008). A draft specification (as of this writing) is for the mass of the full container to be 200 g or less. Because the mass of the contents will be uncertain, it is likely that the science team will fill it to somewhat less than capacity—to, say, 180 g instead of 200 g.

The cache and rover will not be sterilized, but any organisms on the MSL cache and rover and in MSL's assembly, test, and launch environments will be inventoried via genetic methods. The MSL Project Science Group will direct caching operations and sample selection. The current strategy is to collect samples representative of the common rock and mineral types encountered by MSL during its traverse rather than specifically targeting "unusual" finds.

Potential consequences of the MSL cache for MSR. The ND-SAG evaluated several major impacts that the MSL cache might have on the design of the first MSR mission. The following 3 sets of questions and answers summarize the outcome of these deliberations. These answers draw substantially from the findings of Steele *et al.* (2008).

(1) If a cache prepared by MSL (or ExoMars, or any other future mission) is recovered, would MSR necessarily acquire additional samples to achieve its key scientific objectives, or would the samples in the cache be sufficient? If additional samples are required, then the MSR spacecraft must have an independent sample acquisition capability.

Discussion. *The cache's samples have the advantage that they might be collected from a wider geographic area than is possible by MSR. This is particularly true for the MSL rover, which has a nominal mobility range that might be an order of magnitude higher than that of an MSR rover. For whatever reason, MSL might discover and collect unique samples that the MSR could not collect on its own. However, the MSR mission might not be able to retrieve the MSL cache. For example, the MSR spacecraft might land too far away, the MSL rover might end its mission in an inaccessible location, or the cache itself might be in a state that would render it irretrievable.*

MSL's cached samples will be limited to small rocks that its scoop could retrieve from the martian surface. Isolated small rocks might be heavily weathered. Several of the MSR objectives require unaltered samples from rock interiors.

The present design of the MSL sample collection and caching system will not permit the assembly and packaging of all the sam-ples necessary to address the scientific objectives proposed for MSR in this report. The cached samples will be neither labeled nor separated from each other; therefore, the identity of each sample and, therefore, the information about its environmental context might be obscured during caching of the samples. Loss of context data would significantly reduce the science return, particularly for the high priority life-related objectives. Because the cache samples are not to be individually encapsulated, any mechanical disruption during transportation back to Earth might intimately mix the samples and contribute further to the loss of their individual identities.

The standards for organic contamination and planetary protection for the MSL and MSR missions would probably be different (as of this writing, the MSL contamination thresholds are known, but those for MSR are not). The MSL sampling system will not be sterilized. If the MSL cache harbors biological material whose origin could not be determined (Is it from Mars? Or is it earthly contamination?), planetary protection protocols will require that the returned cache samples be sterilized. Stringent sterilization procedures would severely degrade the scientific value of these samples for several of the MSR scientific objectives.

Finally, the MSR mission should be able to respond to any discoveries whose follow-up would require samples other than those in the MSL cache.

Accordingly, the ND-SAG found that the MSR landed spacecraft should have the capability to collect at least some of the samples to be returned by itself.

(2) If the MSR spacecraft must have sample acquisition capability, does the specific nature of that capability depend on whether it would attempt to recover a cache?

Discussion. *The MSL cache could substantially improve the MSR return if certain scenarios occur. For example, if the time available for MSR surface operations becomes severely limited, it might be able to collect a relatively small number of samples on its own, and the MSL cache would become especially important.*

According to current plans, the mass and volume of the MSL or ExoMars caches are estimated to occupy about one-third of the proposed returned sample capacity. Therefore, MSR must acquire either two-thirds or all the returned samples. As discussed above, the MSR spacecraft must have the capability to collect all the sample types of interest.

The design of the sample acquisition system of MSR, therefore, would be independent of the decision to recover either the MSL or the ExoMars caches. Note that a key consideration in this analysis is whether a given kind of sample discovered by MSL would be sufficiently useful in an Earth-based laboratory if stored in the cache or whether it would be preferable to have MSR recollect it.

(3) If MSR returns to a previously visited site (*e.g.*, those of MSL, ExoMars, MER, or other?) where the geologic terrain has been characterized previously to some extent, would the landed instrumentation required for MSR differ from that required to visit a new site?

Discussion. *MSL will carry a highly capable* in situ *laboratory that will be able to characterize the samples and their geologic context in many ways and with superior precision and accuracy. MSL has 10 instruments, including highly capable chemical and mineralogical detectors. It is unlikely that MSR would carry an*

instrument package of this quality. Therefore, the geologic context of the MSL site will be significantly better understood than any other site that the MSR rover might visit. This same argument will also apply to the site visited by ExoMars and, to a lesser extent, the 2 MER sites (Meridiani and Gusev Crater).

There are differences in perspective, however, within the ND-SAG regarding how closely the MSR rover would have to follow the footsteps of a previous rover to take advantage of that previously acquired information. Opinions range from the view that sampling the same stratigraphic bed would be adequate to the view that the same drill hole must be resampled. The further the MSR rover departs from the tracks left by the previous rover, the more important it would be for MSR to have its own instruments to guide its sampling operations. In addition, the presence of instruments on MSR would allow the mission to follow up on unexpected discoveries or to pursue scientific questions that were not addressed by the previous mission.

There is also a concern about contamination should MSR revisit sites. The MSL contact instruments and tools would be decontaminated to a level that allows for the confident detection of martian organics if present, but this is not true of MER. Does this mean that we would need to avoid sampling directly any location previously sampled by MER or MSL? If so, returning to a MER site may not provide the benefit of a reduced payload because, if we want to sample "sister" materials rather than the exact same materials, we might need a fairly sophisticated instrument payload rather than a minimal one. This topic needs further discussion by the community.

Expected contribution of MSL cache samples to the scientific objectives for MSR. Steele *et al.* (2007) assessed

the expected scientific value of the MSL cache. Their results are summarized with respect to the 11 candidate scientific objectives for MSR in Table 10. For Objectives 7 (Regolith), 10 (Gas chemistry), and 11 (Polar), the MSL cache would not make any contribution because it will not have the capability to acquire and store regolith, atmosphere, and ice samples.

For the rest of the MSR scientific objectives, the contribution of the cached samples would likely be "minimal" to "some," depending on which MSL encounters are used and the nature of the samples selected for caching. The priorities for additional sampling by MSR reflect the comparison of the objectives for the MSL cache and the MSR mission and are summarized in Table 10.

In its discussions both internally and externally, ND-SAG has observed that the 2 main sectors of the Mars scientific community that would be able to make the most use of returned samples—namely, astrobiologists and geologists—tend to view the strengths and limitations of the MSL cache differently. For our astrobiological objectives, the limitations are a major concern, whereas, for at least some geologists, the strengths are more important. For MSR to maximize its science return, the samples need to serve the needs of *both* astrobiology and geology, and we encourage all sectors of the community to be sensitive to other points of view.

In summary, for each of the 11 candidate scientific objectives for MSR, ND-SAG concludes that the expected contribution from the cached samples alone would not be sufficient to achieve the main scientific objectives proposed and that additional sample acquisition/packaging by MSR would greatly enhance the science return. The MSL cache

TABLE 10. RELATIONSHIP OF THE MSL CACHE TO PLANNING FOR MSR

		MSR Scientific Objective			None	Minimal	Some	Sufficient to answer main questions?	Priority of additional sampling by MSR
Ref.	Goal	Nickname	Relative priority	Main types of required samples					
1	I	**Habitability**	H	Hydrothermal, sed.		X		NO	V. HIGH
2	I	**Prebiotic, life**	H	Hydrothermal, sed.		X		NO	V. HIGH
3	III	**Water/rock**	H	Hydrothermal, Low T W/R			X	NO	HIGH
4	III	**Geochronology**	H	Any rocks, some need to be unaltered			X	NO	HIGH
5	III	**Sedimentary record**	H	Sedimentary			X	NO	HIGH
6	III	**Planetary evolution**	M	Igneous suite			X	NO	MEDIUM
7	III	**Regolith**	M	Regolith samples	X			NO	V. HIGH
8	IV	**Risks to human explorers**	M	Regolith and dust samples		X		NO	HIGH
9	I	**Oxidation**	M	Depth-resolved suite		X?	X?	NO	TBD
10	II	**Gas chemistry**	M	Atmosphere, rocks	X			NO	V. HIGH
11	II	**Polar**	M	Ice samples	X			NO	V. HIGH

The "Expected contribution by MSL, ExoMars caches" spans the None, Minimal, Some columns.

H, High priority; M, Medium priority.

For MSL Objective 8 (Risks to Human Explorers), there is a need to acquire both regolith and dust samples. Because samples in the MSL cache will be exposed to the martian environment during the period of time between MSL and MSR, the samples would be covered with dust. Although this dust could be extracted after return to Earth, the amount would be very little.

For MSL Objective 9 (Oxidation), the degree of relevance of the cached samples depends largely on the design (including depth range) of the ExoMars drilling system and the capability of ExoMars to cache those samples.

has the potential to increase the diversity of the samples; however, it would imply a larger complexity for MSR in operations and possibly a larger mobility.

> FINDING: It is extremely important that MSR have the capability to select and acquire its own samples, even if the decision is made to recover a cache aboard the MSL or ExoMars spacecraft.

VI-J. Planetary protection

The purpose of planetary protection is to prevent forward contamination of other Solar System bodies (in this case, Mars) by Earth organisms and to prevent harmful contamination of the Earth's biosphere by extraterrestrial organisms. The requirements associated with planetary protection are a critically important aspect of planning MSR. Although there are many planetary protection issues related to MSR, ND-SAG identified 2 topics of particular significance to the scientific value of MSR: (1) The relationship of MSR to "special regions" and (2) The effects of possible heat sterilization of the sample.

In this area, we need to be especially careful to distinguish our discussion of MSR in general from planning for the first MSR.

(1) How important is it to hold open the option of sending MSR to a planetary protection "special region"?

In the past few years, a new category of planetary protection has been defined, which is of particular interest to astrobiologists and the search for modern life. These are "special regions." Special regions were defined in order to provide extra protection to martian environments where terrestrial microbes could propagate (COSPAR, 2002, 2005). In simple terms, special regions have been interpreted to be environments with recent liquid water, and this has been quantitatively refined as locations where 2 environmental conditions are simultaneously met: the temperature is greater than $-20°C$, and the activity of water is greater than 0.5 (MEPAG SR-SAG, 2006; COSPAR, in preparation). Such environments, if they could be identified, would be very attractive targets for MSR because of the potential for extant indigenous martian life.

Accessing and sampling special regions is permitted by planetary protection policy. Doing so would require the sterilization of the spacecraft components that penetrate the special region. For missions that access a special region by means of roving, reaching, or drilling, the subsystems that penetrate the special region would need to be sterilized. For missions that land within a special region, or missions where a special region is present within the landing error ellipse, the entire landed system would need to be sterilized because of the potential of a spacecraft failure and breakup during EDL. In either case, MSR development would be significantly more complex in an engineering sense and, thus, increase mission cost and risk.

At the time of this writing, no martian environment—neither surface nor subsurface—has been identified that is known to meet the technical thresholds for a special region.

However, there are several kinds of environments that exist on Mars for which there is ambiguity as to whether they meet the threshold conditions for "special region" (*e.g.*, mid-latitude gullies, pasted-on terrain). For the purpose of planetary protection, which requires a conservative approach, pasted-on terrain is treated as if it is "special," given that it cannot be shown to be "not special." In addition, MEPAG SR-SAG (2006) pointed out several kinds of geologic environments that, if discovered on Mars by future researchers, could qualify as special (active volcanoes, hydrothermal vents, very young large craters).

For the purpose of planning MSR, it is important to recognize the difference between the view of planetary protection policy-makers about an environment with an ambiguous status (if there is a question, be conservative and treat as if special) and the needs of the scientific community (we need a high degree of confidence that the samples we want will be at the site selected; therefore, MSR is not the right choice for a mission to be probing sites that have major uncertainty).

Discussion—planning for the first MSR. The reality is that we cannot at present credibly propose that the objective of the first MSR should be to find extant martian life and return it to Earth—we don't know where to go or what to sample. We have no information on the environmental habitability factors for unknown martian life-forms. Our best guess is that the most favorable environment would be one with liquid water (which would qualify as a special region), but we have not yet made that discovery. For these reasons, proposed Scientific Objective 2 of this report is phrased "assess the evidence for prebiotic processes, past life, and/or extant life." The specific strategy for how to achieve this is left up to future landing site selection committees and other such planning teams. Note that, since prebiotic chemistry and the possibility of past life could be evaluated without the need to go to a special region, special-region access is not required to achieve this objective. The objective could alternatively be achieved through the study of ancient environments and their geologic products (*e.g.*, sedimentary, igneous, and hydrothermal rocks), for which knowledge of their distribution is much more confidently known.

However, retaining the option to sample a special region with the first MSR would be valuable scientifically in the sense that it may allow us to respond to the discovery of liquid water within the next 5–10 years. Thus, for the first MSR mission, this question boils down to balancing the probability of making such a discovery against the increased cost of mission development (the development cost would be incurred whether the mission is eventually sent to a special region or not). This trade is best evaluated by a joint science-engineering team that could specifically evaluate both the cost and the benefit.

ND-SAG additionally observes that MEPAG SR-SAG (2006) presented very convincing arguments that, for thermodynamic reasons, the most prospective part of Mars for near-surface modern liquid water is the latitude band 30–60° (both north and south latitude), and that it is almost impossible for liquid water to exist equator-ward of 30° latitude. If MSR adopts equatorial landing site restrictions for EDL reasons, there would be little reason to believe that special region access capability could actually be used.

Note that whether MSR would or would not be sent to a special region is unrelated to whether the returned samples would be evaluated for extant martian life—they assuredly would be, even if they do not come from special regions.

FINDINGS:

- ND-SAG finds that a scientifically compelling first MSR mission could be designed without including the capability to access and sample a special region.
- It would be desirable scientifically to retain the option of responding to a post-2007 discovery that changes our understanding of martian special regions. However, the same could also be said of many other possible ways to enhance MSR—deciding which would be a prudent investment would entail cost-benefit comparisons of the various options and consideration of budget availability.
- Based on our understanding of Mars as of 2007, unless MSR had the ability to land poleward of 30° latitude, access very rough terrain, or achieve a significant subsurface penetration (*e.g.,* >5 m), MSR would likely not be able to make use of incremental special regions capability.

(2) What would be the effect on the scientific value of the samples if they are heat sterilized prior to Earth return?

Discussion—planning for the first MSR. Since we have no information about martian life, beyond a reasonable hypothesis that it is most likely to be carbon-based, the only way to be confident of destroying it is to destroy the chemicals on which that life depends (SSB, 1997). This has been interpreted to involve either heating the entire sample to 500°C (half a second at the most protected location is presumed to be adequate) or some combination of high temperature and hard radiation (SSB, 1997; Conley, written communication, 2008). Treating the samples this harshly would have severe negative impacts on the scientific usefulness of the returned material:

(a) Destroy or alter organic material within the sample, including components such as amino acids, polycyclic aromatic hydrocarbons, and paraffins, needed to evaluate hypotheses that involve prebiotic chemistry, past life, and modern life.
(b) Destroy or alter many hydrous minerals such as clays, sulfates, and hydroxides that are essential to interpreting the aqueous history of Mars.
(c) For samples that are not encapsulated, components released from one sample could react with other samples, which would cause the samples to no longer be representative of the martian environment.
(d) Adversely affect studies on possible (unknown) oxidant phases in regolith samples.

In addition, from a planetary protection standpoint there is no rationale to attempt sterilization of samples prior to Earth return. Since no method for the sterilization of putative martian life has been validated, it would be very difficult to justify allowing the return of uncontained samples regardless of how they had been treated prior to Earth entry (Conley, written communication, 2008). ND-SAG concludes that heat sterilization of the samples would entail major negative consequences without any real benefit.

VI-K. Contamination control

Controlling the amount of contamination of the samples by both inorganic and organic species would be essential for realizing the potential scientific value of MSR. MSR would need to have specific contamination requirements in at least 3 areas: (1) Earth-sourced organic molecules, (2) Earth-sourced inorganic substances, and (3) live Earth-sourced organisms. Although dead Earth-sourced organisms would also be of interest (in the event that they are detected by molecular methods), they would be covered in category 1. For organic compounds, Mahaffy *et al.* (2004) proposed an overall limit of 40 ppb, with sub-limits for each of 6 main classes of organic molecules of interest, and MacPherson *et al.* (2005) recommended that this be reduced for MSR by a factor of 4, to a total of 10 ppb. Although modern instrumentation may have the capability to detect much lower levels of organics, achieving a significantly lower allowable contamination limit may be impractical, as may the realization of lower organic levels in blanks used during the sample analysis. For inorganic contaminants, MacPherson *et al.* (2005) recommended that the levels be set at 0.1% of the concentration in Shergotty and Nakla, 2 of the martian meteorites. This led to the calculation of Table 7 in their report, which has specific recommendations for about 30 elements of interest. For live terrestrial organisms, a draft planetary protection requirement is a 10^{-2} probability of a single round-trip organism. We are not aware that the scientific community has ever proposed a requirement stricter than this. All of the above are the starting point for future discussion as science priorities in this area are further refined.

It would also be important that we design an effective strategy for the use of witness plates on MSR to help distinguish carbon compounds in the returned samples from contamination introduced during spacecraft operations or sample processing on Earth. We know that sample contamination happens in the terrestrial environment, regardless of how carefully the sample is treated. For example, handling of lunar and meteorite samples has resulted in the introduction of contaminants, which include the following: (1) xylan, an amide-based compound found in lubricant for bolts in the lunar processing cabinets (Wright *et al.*, 1991,1992); (2) phthalates and siloxanes (Steele *et al.,* 2001); and (3) epsilon amino n-caproic acid, which forms during hydrolyis of nylon bag material used to contain carbonaceous chondrites (Glavin *et al.,* 2006). Terrestrial microbes are known to be able to propagate on martian meteorites (Steele *et al.*, 2000; Toporski and Steele, 2007). A key to identifying and avoiding contaminants such as these is to archive any potential contamination sources during the spacecraft and hardware design and construction, a process which has heritage from several sample-return missions including Apollo, Genesis, Stardust, and Phoenix. However, this step must be planned for in advance.

> FINDING: **Heat sterilization of the samples would have major negative consequences without any real benefit.**

VI-L. Documented sample orientation

The scientific value of the returned collection could be improved if sample orientation is documented for at least some of the samples. The primary use for this sample attribute would be in paleomagnetic studies (see Appendix II; Investigations III-A-10 and III-B-2), but it may also be useful in interpreting paleoflow directions for sedimentary rock samples. The scientific need could be met if the sample orientation is known to within ~10 degrees.

The orientation measurements could, in principle, be determined through a combination of telemetry and imagery (the same technique is used on MER, where orientation precision is determined to within a few degrees). Telemetry includes overall rover orientation from the IMU and joint angles from the arm. Imagery includes the documentation images of the scientific target as well as operational imagery that shows the arm in place and the position of the instruments (and corer) as the samples are obtained. This information is already required for sample documentation and safety monitoring of arm operations; therefore, determining the orientation should not add any additional requirements on the system. Finally, we need to know the rotational orientation of the core sample. This may be available for indurated samples by comparing images of the surface with MI images taken before drilling. Although not all samples would preserve the top after drilling, enough may do so to be sufficient to meet the science goals of the mission. Of course, alternative methods for marking the rotational orientation might be superior and should be sought.

VI-M. Program context, and planning for the first MSR

MSR would not be a one-time stand-alone mission. During the course of deliberations by ND-SAG, it became evident that relationships must be more clearly defined between MSR, the Mars Exploration Program (MEP), and the eventual human exploration of Mars.

The MEP lays out a logical progression of missions that build upon the past and lead to the future. In that sense, the recent, current, and planned missions have already contributed (and would continue to contribute) to a superior first MSR mission (see Section IV-A). We thus believe that a first MSR mission in the next decade would be far better scientifically than any MSR mission that might have been implemented earlier. This validates NASA's foresight in establishing the MEP many years ago and its belief that Mars holds a special place in planetary exploration. The ND-SAG anticipates that such a productive return on investment would continue after the first MSR mission: there is no doubt that the analyses of the returned samples would significantly alter our understanding of Mars and greatly enhance our interpretation of current and future remote-sensing data. This conclusion has been "validated" by the Apollo program in which the results from the Apollo 11 returned samples directly and rapidly impacted subsequent Apollo missions and led to the establishment of many of the scientific objectives for the current spate of lunar robotic missions.

For the first MSR mission, the need to keep the mission from becoming overly complex in an engineering sense must be weighed against retaining the essential attributes that contribute to the scientific value. As input to these trades, the ND-SAG team has summarized in Table 11 the various attributes discussed in this report that would improve the scientific value of MSR, along with a preliminary assessment of the impact of these attributes on mission engineering. Since there are legitimate differences of opinion within the scientific community on the priority of these attributes, and the planning for a possible MSR is still in its early stages, rather than try to reach consensus on a single set of priorities, we have opted to present 3 example priority positions, as shown in the columns on the right in Table 11. These priority positions illustrate both the commonalities and the differences in how different sectors of the scientific community value these attributes.

The question naturally arises as to what follows MSR in the MEP. First, we do not consider MSR to be a single-mission event. The great diversity of Mars makes it probable that not all MSR objectives could be achieved at one sample site. Landing site engineering constraints for the first MSR mission prohibit going to certain terrains, such as polar regions and rough topography (*e.g.*, the gullies of "uncertain special regions" or "special regions"). The data gleaned from the first MSR mission would likely stimulate the desire to conduct additional MSR missions.

There is an aspect of a "second MSR mission" that merits our attention, to wit, the MEP may decide, for reasons of *program* risk reduction, to advocate replicating the riskier elements of the mission, *e.g.*, landing and ascent systems. If such appears prudent and affordable, we could today make a convincing case that returning samples from 2 substantially different sites on Mars would be eminently prudent. The living example of this risk-reduction philosophy is the MER mission, for which the NASA administrator chose to send 2 landers.

The ND-SAG emphasizes that, however important, the first MSR would not be the finale of a science-driven MEP. We know now that other mission types need to be considered for opportunities immediately following the first MSR. There are already high-priority proposed and studied mission concepts that are relatively independent of MSR results (*e.g.*, network missions, orbital science) and could be implemented immediately after the first MSR. Indeed, it is virtually inevitable that the results of the first MSR will lead to new proposals for non-MSR orbital and surface science missions.

The MSR mission would have a significant relationship to eventual human exploration. As shown both in the MEPAG Goals and in this study, information gleaned from the returned samples would be directly related both to the health and well-being of astronauts on Mars and to reliable operations on the martian surface. There is an associated indirect, yet important, aspect: the detailed knowledge obtained from the returned sample would inevitably inform as to what science astronauts would do at Mars and how they would do it. For these reasons, an MSR mission would probably be required at the landing site eventually selected for human exploration (which may or may not be a prior MSR site). Again, we refer to the Apollo missions in which post Apollo 11 mission science was altered in response to findings from re-

TABLE 11. SCIENCE PRIORITY OF ATTRIBUTES OF THE FIRST MSR

Attribute judged to improve scientific value of MSR	Range of parameter	Perceived impact on mission engineering	Proposed first MSR priorities		
			Yugo	Chevy	Lexus
Sample size, g	10	Minimal	H: 10	H: 10	H: 10
Number of rock samples (new site)	20 to 28	Moderate	H: 20	H: 24	H: 28
Regolith and dust mass, g	45 to 125	Moderate	H: 125	H: 85	H: 45
Total sample mass (previous cache not returned)	>325	Moderate	H: >325	H: >325	H: >325
Contamination control	TBD	Major	H: TBD	H: TBD	H: TBD
Samples encapsulated	Yes/No	Moderate	H	H: Yes	H: Yes
Mobility, km	2 to 10+	Major	H: 2	H: 6	H: 10+
Mini-corer	Yes/No	Moderate	H: Yes	H: Yes	H: Yes
Heat sterilization	Yes/No	Major	H: No	H: No	H: No
Science instruments, number*	4 to 5	Moderate	H: 4	H: 5	H: 5
Sample acquisition time, months	6 to 18	Major	H: 6	H: 12	H: 18
Isolated gas sample compressed	Yes/No	Moderate	M: Yes	H: Yes	H: Yes
Sample temperature < +20°C	Yes/No	Minimal	H: Yes	H: Yes	H: Yes
Sample temperature < −20°C	Yes/No	TBD	L: Yes	L: Yes	H: Yes
Sample orientation known	Yes/No	None	L: Yes	L: Yes	H: Yes
Two landers?	Yes/No	Major	L: Yes	L: Yes	H: Yes
Option to visit special region	Yes/No	Major	L: Yes	L: Yes	M: Yes
Acquire previous cache	Yes/No	Major	TBD	TBD	TBD
Deep drill	Yes/No	Major	TBD	TBD	TBD

H, High priority; M, Medium priority; L, Lower priority.
*Revisiting a previously characterized site might require only 2 instruments.

turned samples. Lastly, there would be the "proof-of-concept" element of MSR in which the demonstration of the round-trip to Mars, with a successful Earth return, will help to bolster public understanding and conviction that it is indeed feasible for humans to make that sojourn.

VII. Summary of Findings and Recommended Follow-Up Studies

Additional discussion is recommended in the following areas:

(1) *MSR landing site selection process and timing.* How would the specific candidate landing sites for MSR be identified and screened for safety? Which sites optimize the science return by effectively addressing the most MSR scientific objectives? Would it be prudent to use the instruments on MRO for this purpose while the orbiter is still healthy? We need to take into consideration the expected availability of orbital instruments during the second decade.

(2) *Contamination limits.* All the arguments related to contamination limits and priorities discussed above in Section VI-K will need to be reconsidered. Substantial amounts of information now exist (including unpublished data) about contamination relevant to many different missions or sample collections—Antarctic meteorites, lunar samples, Stardust, Genesis, and perhaps soon Hayabusa. In addition, we will need to consider experience and results from the 2007 Phoenix Mars mission, the 2009 Mars Science Laboratory, and the 2013 ExoMars mission. It would be useful to compile a summary for these different cases with an aim to identify common problems, solution philosophies, and lessons learned. Note that, for scientific purposes, contamination management planning must address flight system activities as well as sample handling in the SRF, post-SRF curation, and PI laboratories. There is no point in keeping the samples substantially cleaner during any one of these phases than during the others—we need a contamination management plan for the entire life cycle of the samples.

(3) *Depth of subsurface access.* A major open question for MSR is the nature of the relationship between the oxidizing surface zone and the inferred reduced subsurface zone. What is the depth scale of this gradient into the near subsurface? How does this depth scale vary as a function of the permeability of the particular subsurface material? As we acquire relevant new information by way of ongoing missions, new missions, or from new modeling methods, this question needs to be reconsidered. We will require assistance to make informed decisions regarding the hardware necessary to access subsurface materials during the MSR mission.

(4) *For core samples: length vs. diameter.* This report recommends that a mini-corer be utilized to acquire rock samples and that these samples must be larger than about 10 g (or, if the engineering requirement is defined in terms of volume, about 3.5 cc). However, the ND-SAG team did not attempt to evaluate the optimal combination of length and diameter of these core samples. Preliminary thought within the ND-SAG team was that a mini-core length of about 5 cm would be desirable, but more systematic analysis is required.

(5) *Strategy for splitting the samples in the SRF.* A strategy should be devised in advance for splitting the rock samples that arrive intact at the SRF. For the purpose of planetary protection, it would be necessary to take statistically significant subsamples in order to reach conclusions that could be applied to the entire sample. The decision on how the samples are subdivided would affect the subsequent scientific investigation plan.

(6) *Relationship between landing site targeting precision, minimum roving distance, and time on the surface.* If the landing error ellipse has a radius of 3 km, and the sample acquisition traverse is about 2 or 2.5 km, then the total rover distance would be 8.5 km (3 + 3 + 2.5) (given, of course, that the landing site is a "go-to" site). If landing site targeting precision is reduced to 1 km, this would reduce range to 4.5 km (1 + 1 + 2.5). A relatively firm time constraint might be imposed by the limitations on thermal cycling of the MAV; accordingly, it would have to launch within 12 months. This is independent of planetary alignment considerations. Given estimates of rover distance per day, time to use the instruments to do sample selection, and the time to drill and encapsulate each of the rock samples, there is a possibility that all the work needed cannot fit within the allowable 12 months. These issues would be more severe in ND-SAG's "Case A," where MSR is sent to a virgin site (time would be required to determine the geologic context). Thus, it seems likely that the relationships between time on the surface, rover mobility range, landing site targeting precision, and spatial distribution of samples will need more detailed study. The Mars exploration community should develop strategic ground-operation scenarios, *e.g.*, conduct multiple sample collection sorties with periodic sample deliveries to MAV.

(7) *Preparation of a Design Reference Mission.* It would be helpful to prepare a Design Reference Mission that would summarize how we would achieve the following: (1) collect samples and characterize the site, (2) address the key questions that this exploration was designed to answer, and (3) respond to new discoveries. We suggest that we do such a study for the Columbia Hills. Such an analysis would tell us how much documentation would be needed to understand the context of a site, how much sample should be obtained to characterize a specific type of rock (or process), and what distances should be traveled to obtain the samples for MSR that would be needed to address key scientific goals and objectives.

(8) *Engineering/cost studies of each of the factors indicated in Section VI.* Each of the factors described in Section VI of this report should be evaluated more rigorously for their engineering and costs. (For example, regarding Number of samples—optimal number of encapsulated samples; potential value of an additional large "MSL-like" chamber for local regolith plus "durable" rock chips, etc.).

VIII. Acknowledgments

Appendix I (ND-SAG Charter)

Science Issues and Priorities for a Next Decade MSR Science Analysis Group (ND-SAG)

Introduction

On July 10, 2007, Dr. Alan Stern, AA-SMD, described to the participants in the 7th International Conference on Mars his vision of achieving MSR no later than the 2020 launch opportunity. He requested that the details of this vision be analyzed over approximately the next year for financial attributes, for scientific options/issues/concerns, and for technology development planning/budgeting.

MEPAG has been asked to contribute to this effort by preparing an analysis of the science components of MSR and its programmatic context. To this end, MEPAG hereby charters the Next Decade MSR Science Analysis Group (ND-MSR SAG). The output of this team will constitute input to a Mars program architecture trade analysis.

Starting assumptions

(1) Assume that the sample return mission would begin in either 2018 or 2020.
(2) Assume that MSL will launch in 2009 and will prepare a simple cache of samples that is recoverable by the MSR rover. Assume that ExoMars may carry a similar cache.
(3) Assume that a post-MSL sample acquisition functionality would be associated with MSR. This functionality may either be landed at the same time as the sample return element of MSR, or it may be separated into a precursor mission.
(4) Assume a stable program budget, about $625 million per year, growing at 2% per year.

Requested tasks

(1) Evaluate the science priorities associated with the design of the sample collection to be returned by a next decade MSR mission.
   (a) *Returned sample characteristics.* Based on the 2006 version of the MEPAG Goals Document, which scientific objectives could be achieved/supported by sample return; and, for each objective identified, what kind of samples would be necessary to answer the questions that have been posed?
      (i) Estimated number of samples
      (ii) Physical condition of samples
      (iii) Contamination limits
         • Earth-sourced organic contamination
         • Inorganic contamination by sampling hardware and/or sample containers
         • Cross contamination between martian samples
         • Contamination by martian airborne dust
      (iv) Environmental controls needed for storage on the surface and during return to Earth
   (b) *Samples acquirable at a single operational site.* Assuming that it is not possible to acquire all the samples of interest at one landed operational site, prepare models for different kinds of geologic terrain showing how large a fraction of the samples of interest could reasonably be acquired at each, and, by derivation, the kinds of scientific objectives that would be realistically achievable in a single sample-return mission.
(2) What are the dependencies of the achievable scientific objectives on the following:
   (a) The sample acquisition functionality of the post-MSL MSR-affiliated sample acquisition functionality?
   (b) The instrument complement of the post-MSL MSR-affiliated sample acquisition functionality to provide information to support sample collection decisions considered ideal and minimal instrumentation sets.
   (c) Mobility and lifetime of surface operations for the post-MSL MSR-affiliated sample acquisition functionality
(3) Analyze what critical Mars science could be accomplished in conjunction with and complementing MSR.
(4) In planning MSR to launch in 2020, it is expected that at least one launch opportunity would need to be skipped for the MEP to remain within its financial resources. Given the launch opportunities of 2013 and 2016 (2018 being skipped), what would be the first and second priorities for strategic missions in the next decade?
(5) As necessary, support MSR science planning as requested by the IMEWG MSR study.

Timing

The SAG should begin its discussions as soon as possible. Results are requested in 2 phases, which will have different levels of fidelity. An interim report is requested in early

November, 2007, and a draft report by December 15, 2007. Assume that this report will be discussed in detail by MEPAG at its next full meeting, tentatively February 20–21, 2008, and that the final report will consider feedback received in this exchange.

Report format

The results of this SAG should be presented in the form of both a PowerPoint presentation and a text white paper. Additional supporting documents can be prepared as needed. After the report has been accepted, it will be posted on a publicly accessible website.

The report may not contain any proprietary information or material that is ITAR-sensitive.

Michael Meyer, NASA Senior Scientist for Mars Exploration, NASA HQ
David Beaty, Mars Exploration Directorate Chief Scientist, Mars Program Office, JPL
Rich Zurek, Mars Exploration Program Chief Scientist, Mars Program Office, JPL
Jack Mustard, Brown University, MEPAG Chair
July 24, 2007

Appendix II: Analysis of the Use of Returned Martian Samples to Support the Investigations Described in the MEPAG Goals Document

This appendix is approximately 100 pages in length and is presented as a separate document. To view, refer to the following:

MEPAG ND-SAG. (2008) Science priorities for Mars Sample Return—Appendix II: Analysis of the use of returned martian samples to support the investigations described in the MEPAG Goals Document. Unpublished white paper, posted March 2008 by the Mars Exploration Program Analysis Group (MEPAG). Available online at http://mepag.jpl.nasa.gov/reports/ndsag.html.

Appendix III: The First Mars Surface-Sample Return Mission: Revised Science Considerations in Light of the 2004 MER Results

Authorship: Mars Sample Return Science Steering Group II (Glenn MacPherson, Chair)
Report Date: February 16, 2005
This appendix is 62 pages in length and is presented as a separate document. To view, refer to the following:

MacPherson, Glenn, and the Mars Sample Return Science Steering Group II (2005). Science priorities for Mars Sample Return—Appendix III: the first Mars surface-sample return mission: revised science considerations in light of the 2004 MER results. Unpublished white paper, posted March 2008 by the Mars Exploration Program Analysis Group (MEPAG). Available online at http://mepag.jpl.nasa.gov/reports/nd-sag.html.

Appendix IV: Science Traceability from MEPAG Goals (2006 version) to Candidate MSR Scientific Objectives

The MEPAG scientific Investigations (left) are color coded into the following 4 areas:

(1) Gold: Has been significantly addressed by missions to date, but MSR would still contribute.
(2) Green: High priority for MSR with significant MSR contribution.
(3) Blue: MSR would contribute.
(4) Grey: Would not be significantly addressed by MSR.

The candidate MSR scientific objectives (right) are color coded purple for high priority and pink for medium priority.

The arrows trace the linkage from the MEPAG scientific Objectives and Investigations to the candidate MSR scientific objectives. Green areas indicate linkages from MEPAG high-priority Investigations for MSR to candidate objectives. Blue arrows indicate lower-priority MSR contributions.

Note that the arrows originate both at the MEPAG Investigation and Objective levels. Where they originate at the Investigation level, they link the specific Investigation to the MSR candidate objective. Where they originate at the MEPAG Objective level, they indicate that several of the Investigations in that Objective address the MSR candidate objective.

Appendix V: Comparison of the Analysis of the Martian Atmosphere by MSL and in a Returned Sample on Earth

Krypton and xenon

The major questions to be addressed are the starting isotopic compositions and to what extent they have been mass fractionated. Other questions involve the amounts of added nuclear components, which include ^{129}Xe from decay of extinct ^{129}I, ^{80}Kr and ^{82}Kr from neutron capture on Br, heavy Xe (*e.g.*, ^{136}Xe) from fission of extinct ^{244}Pu, and possibly light Xe (*e.g.*, ^{124}Xe) from cosmic ray-induced spallation. Within our present knowledge, Kr isotopes appear fractionated by <7% and possibly much less across the 78–86 amu mass range. Xe isotopes appear to be mass fractionated about 40% across the ^{124}Xe to ^{136}Xe mass range, or ~4% per amu. In the analysis here, we assume *each* Xe and Kr isotopic ratio can be measured by MSL to at least 1%, but possibly 0.1% on Earth.

For Xe, MSL's 1% precision in ^{124}Xe/^{136}Xe or ^{126}Xe/^{136}Xe could answer the question of the Xe starting composition. Also, a 1% precision in ^{129}Xe/^{132}Xe would give the ^{129}I decay component to satisfactory precision. However, characterizing the smaller anticipated Xe isotopic effects arising from GCR spallation and fission of Pu and U require a precision better than 1%, and their characterization could yield better data for the initial Xe composition than that likely to be determined by MSL.

For Kr, the issue of starting composition may not be made clear by MSL analyses, especially considering that mass 78 is often contaminated and mass 80 and 82 would likely have an added component from neutron capture on ^{79}Br and ^{81}Br. If we must determine the starting composition from the ^{83}Kr/^{86}Kr ratio, and given this ratio only varies in martian meteorites by 2–3%, then a 1% precision on MSL measurement is not sufficient to answer the question of Kr starting composition. Also, knowledge of the exact neutron component of Kr is not obtained from a 1% precision. Measuring these Kr isotopes on Earth to 0.1% precision would give
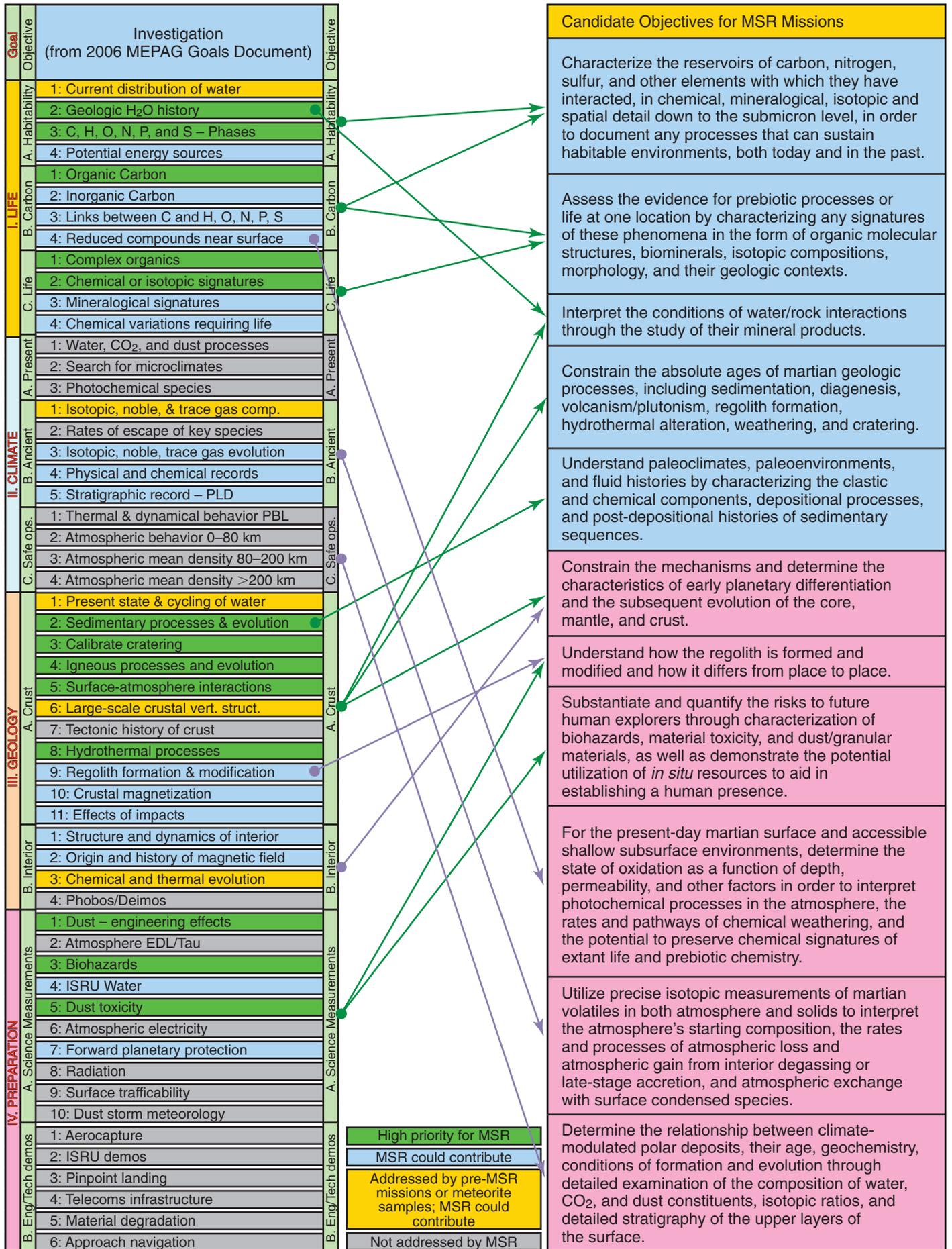
Appendix IV Figure. See description on page 527.

much more information. Thus, a returned Xe sample is of at least modest additional benefit, whereas a returned Kr sample is required to answer the fundamental scientific questions.

Argon

There are 2 main scientific questions: to what extent has atmospheric loss fractionated $^{36}Ar/^{38}Ar$, and how much ^{40}Ar has been added from decay of ^{40}K? These are interacting data sets. We believe the current $^{36}Ar/^{38}Ar$ ratio is ~4, fractionated from a starting ratio of ~5.4 (Bogard, 1997). A 1% MSL precision in measuring this ratio (*i.e.*, 4.00 ± 0.04) would be quite adequate for modeling Ar loss processes. Also, a 1% MSL precision in $^{40}Ar/^{36}Ar$ (*e.g.*, 1800 ± 18) would be quite adequate in determining the amount of radiogenic ^{40}Ar. Thus, there would be modest rationale for a returned Ar sample.

Nitrogen

The main scientific question is the degree of $^{15}N/^{14}N$ fractionation due to atmospheric loss over time. Viking found this ratio to be enriched over Earth by a factor of 1.62 ± 0.16 (Nier and McElroy, 1977). For modeling atmospheric loss processes, a 1% precision is quite adequate, and little would be added from a returned sample.

Neon

The martian neon composition is very poorly known, as is the mixing concentration. Because of neon's low molecular weight, we expect Ne isotopes to have been strongly fractionated during atmospheric loss. For MSL, the analysis of ^{20}Ne will have a problem with interference from doubly ionized ^{40}Ar. SAM will try to generate some information on $^{21}Ne/^{20}Ne$, and it will certainly take a shot at Ne isotope measurement with the GC separation of Ar from Ne, but it is difficult to get a good isotope measurement on a rapidly changing signal. There is very strong rationale for a returned sample.

Methane, volatile hydrocarbon, and sulfur gases

In low concentrations, some trace gases probably could not be returned to Earth without serious alteration. They are better measured on Mars. However, this may not be true of methane, which is relatively inert at ambient and lower temperatures, particularly if the gas sample is isolated from solid martian materials. Methane would be an important measurement target for understanding regional-to-sample-scale isotopic systematics and differentiating abiogenic and biogenic hydrocarbon gas sources (Sherwood Lollar *et al.,* 2002). Also important to distinguishing models of methane formation would be the methane/ethane ratio. Neither of these measurements will be possible with MSL.

C and O in CO$_2$ and H$_2$O

Viking reported $^{13}C/^{12}C$ and $^{18}O/^{16}O$ in CO_2 to only 5% precision (Nier and McElroy, 1997; Owen *et al.,* 1977). There are 2 different scientific questions. First, could we measure mass fractionation due to atmospheric loss? To do so would require precisely measuring not only the atmospheric iso-

topics, but those of condensed phases as well, in order to know starting compositions. The second science goal relates to isotopic fractionations that occur when these atmospheric gases achieve chemical equilibria (including reactions) with condensed phases. Again this would require precisely measuring not only the atmospheric isotopics, but also the isotopes of condensed phases. Many of these isotopic fractionations occur at 0.1–1%, some at much less. Thus to fully utilize the scientific potential inherent in the O and C isotopics in atmospheric CO_2 probably would require their measurement to better than 0.1%. We conclude that sample return of CO_2 would be highly desirable to answer both scientific questions posed. As for H_2O, it occurs in low concentrations in Mars' atmosphere and would likely be altered during sample return. Thus, we conclude that measuring the O isotopic ratio in H_2O would be better done on Mars.

D/H

A very elevated ratio in Mars' atmosphere (about 4.5 times Earth's) has been measured from Earth (Owen *et al.,* 1988). Controversy remains over the D/H in martian meteorites. Leshin and co-workers have suggested that it is enriched perhaps by a factor of 2 over Earth, but Boctor and co-workers have argued it is more like Earth's (Leshin *et al.,* 1996; Boctor *et al.,* 2006). It would be very useful to get the D/H in various hydrated samples. Also, H is known to be rapidly lost from the atmosphere, and this loss over billions of years should produce D/H fractionation even larger than observed in the atmosphere. Thus, the D/H probably varies over time and could be a measure of variations in climate and volcanic degassing. There exists the potential to use the D/H ratio in samples of different ages to examine climatic and degassing episodes on Mars. It would be very useful to get the D/H in various hydrated samples, which should be of greater value in addressing these issues than a more precise determination of the present atmospheric D/H.

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