Mars Science Goals, Objectives, Investigations, and Priorities: 2015 Version

Mars Exploration Program Analysis Group (MEPAG)

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PREAMBLE

The Mars Exploration Program (MEP) has requested that MEPAG maintain what is colloquially referred to as the Goals Document, first released in 2001 (MEPAG 2001), as a statement of the Mars exploration community's consensus regarding its priorities for the robotic Mars flight program. MEPAG regularly updates the document as needed to respond to discoveries made by the missions of the Mars Exploration Program and changes in the strategic direction of NASA. Historically, MEPAG has found that the pace of change in our knowledge of Mars is such that updates are needed on average about every two years (MEPAG 2004; MEPAG 2005; MEPAG 2006; MEPAG 2008; MEPAG 2010; MEPAG 2012, and this document[1]). MEP's intent is to use this information as one of its inputs into future planning, with no implied timeline for conducting the investigations; the rate at which investigations are pursued is at the discretion of the space agencies around the world that provide funding for flight missions. Another forward planning process that is similar in some ways is the National Research Council's (NRC's) Decadal Survey, which is carried out once every 10 years. MEPAG's information constitutes one of many inputs into the NRC's evaluation, and these two organizations operate independently.

This version of the MEPAG Goals Document is organized into a four-tiered hierarchy: Goals, Objectives, Sub-objectives, and Investigations. (Sub-objectives are new in this revision of the Goals Document and allow for refined descriptions of elements of the Objectives, as described below). The Goals are organized around major areas of scientific knowledge and highlight the overarching objectives of the MEP. Expanded statements of the Goals are found in the report, but they are commonly referred to as Life, Climate, Geology, and Preparation for Human Exploration. MEPAG does not prioritize among the four Goals because developing a comprehensive understanding of Mars as a system requires making progress in all three science areas, and the goal of preparing for human exploration is different in nature.

Each Goal includes Objectives that embody the strategies and milestones needed to achieve the Goal. The Sub-objective tier is new and includes more detail and clarity on different parts of Objectives, but covers tasks that are larger in scope than Investigations.

A series of Investigations that collectively would achieve each Sub-objective is also identified. Although some Investigations could be achieved with a single measurement, others require a suite of measurement types, usually requiring multiple missions. Each set of Investigations is independently prioritized within the parent Sub-objective. In some cases, the specific measurements needed to address Investigations are discussed; however, how those measurements should be made is not specified, allowing the competitive proposal process to identify the most effective means (instruments and/or missions) of making progress towards their completion.

Completion of all Investigations would require decades and it is possible that many are so complex that they might never be truly completed. Thus, evaluations of prospective missions and instruments should be based on how well Investigations are addressed and how much progress might be achieved in that context.

[1] All MEPAG Goals Documents can be found at http://mepag.nasa.gov/reports.cfm.

Finally, this updated hierarchy has been augmented with Goal-specific spreadsheets that show the traceability from the Goal to the Investigation level, enabling readers to view the entirety of each Goal “at a glance”. The introduction to each Goal chapter includes a portion of this spreadsheet showing the Objectives and Sub-Objectives for that Goal. The full spreadsheet, down to the Investigation level, accompanies this document as Supplementary Material (Excel/PDF files).

Prioritization

Within each Goal, prioritization is based on subjective consideration of four primary factors (given here in no particular order):

- Status of existing measurements compared to needed measurements
- Relative value of an investigation to achieving a stated objective
- Identification of logical sequential relationships
- Cost/risk/feasibility of implementation

Additional criteria may have been applied within an individual Goal. The specific prioritization scheme used within each Goal is described in the relevant chapter.

Although priorities should influence which Investigations are conducted first, they should not necessarily be undertaken serially, except where it is noted that one Investigation should be completed first. In such cases, the Investigation that should be done first was given a higher priority, even where it is believed that a subsequent Investigation would be more important.

Cross-cutting Investigations

Most of Mars science is, by nature, a cross-cutting endeavour. For example, geological and mineralogical evidence for long-lived standing bodies of water in the ancient past provides a constraint for climate models. Such interrelationships are not readily apparent in the hierarchical structure of this document. Previously, such connections were described only at a very high level in the concluding chapter called “Cross-cutting Strategies” (Section V). In this version of the Goals Document, we augment these high-level strategies by also identifying “Cross-cutting Investigations”. These Investigations are ones that may shed light on Sub-objectives other than the ones from which they are directly derived (either within that Goal, or in another Goal), and they are identified in the spreadsheets that accompany this document. The identification of specific interrelationships at the Investigation level is intended to help members of the scientific and engineering communities identify the broader impacts of research and/or development activities undertaken within or for the flight program.

Additional notes relating to this version (2015) of the Goals Document

New results from the Mars Science Laboratory and ongoing missions (Mars Reconnaissance Orbiter, Mars Express, the Mars Exploration Rover Opportunity, and 2001 Mars Odyssey) were the primary impetus for the latest cycle of revisions and re-assessment of priorities that will help guide the Mars Exploration Program (MEP) forward into the decade of the Mars-2020 mission and beyond. In this revision of the Goals Document, Goals I-III received substantial revisions based on scientific results and a major summary of many aspects of Mars science presented at The Eighth International Conference on Mars, held at Caltech in July 2014 (http://www.hou.usra.edu/meetings/8thmars2014/presentations/). Additionally, although that conference was the impetus for this activity, science results (and outstanding questions) from other conferences, workshops, and the literature have also been taken into consideration. For Goal IV, a revision was necessitated by the advancements in science knowledge of the Mars environment by recent missions, and an effort to bring the Goal IV organization and priorities in-line with the Evolvable Mars Campaign (EMC).

The Goals Committee would like to extend its appreciation to the Integration team who summarized the state of Mars science at the Eighth International Conference on Mars, and who have contributed to the discussions of the Goals Committee: Phil Christensen (Geology), Marcello Coradini (Preparation for Human Exploration), Dave Des Marais (Life), and Rich Zurek (Climate).

Section of the Goals Document	**Last Signif. Update**
Goal I – Determine if Life Ever Arose on Mars	this draft
Goal II – Understanding the Processes and History of Climate on Mars	
Goal III – Determine the Evolution of the Surface and the Interior of Mars	
Goal IV – Prepare for Human Exploration	
Section V – Cross-Cutting Strategies	

Major organizers and contributers to previous versions:

Previous versions of the MEPAG Goals document are posted on the MEPAG website at: http://mepag.jpl.nasa.gov/reports.cfm.

2012 version (posted online 2014): Victoria E. Hamilton, Tori Hoehler, Frances Westall, Scot Rafkin, Paul Withers, Steve Ruff, R. Aileen Yingst, and Darlene Lim

2010 version: Jeffrey R. Johnson, Tori Hoehler, Frances Westall, Scot Rafkin, Paul Withers, Jeffrey Plescia, Victoria E. Hamilton, Abhi Tripathi, Darlene Lim, David W. Beaty, Charles Budney, Gregory Delory, Dean Eppler, David Kass, Jim Rice, Deanne Rogers, and Teresa Segura

2008 version: Jeffrey R. Johnson, Jan Amend, Andrew Steele, Steve Bougher, Scot Rafkin, Paul Withers, Jeffrey Plescia, Victoria E. Hamilton, Abhi Tripathi, and Jennifer Heldmann

2006 version: John Grant, Jan Amend, Andrew Steele, Mark Richardson, Steve Bougher, Bruce Banerdt, Lars Borg, John Gruener, and Jennifer Heldmann

2005 version: John Grant

2004 version: G. Jeffrey Taylor, Dawn Sumner, Andy Steele, Steve Bougher, Mark Richardson, Dave Paige, Glenn MacPherson, Bruce Banerdt, John Connolly, and Kelly Snook

2001 Version: Ron Greeley

GOAL I: DETERMINE IF MARS EVER SUPPORTED LIFE

Objectives	Sub-Objectives
A. Determine if paleoenvironments having high combined potential for prior habitability and preservation of biosignatures record evidence of **past life.**	**A1.** Characterize the prior habitability of paleoenvironments, with a focus on resolving former conditions and processes that influence the degree or nature of habitability in each paleoenvironment.
	A2. Assess the potential of conditions and processes to have influenced preservation or degradation of biosignatures and evidence of habitability, from deposition to time of observation. Identify specific paleoenvironmental deposits and subsequent geological conditions that have high potential to have preserved evidence of individual or multiple types of biosignatures.
	A3. Determine if ancient biosignatures are present.
B. Determine if localities having high combined potential for modern habitability and biosignature presence host evidence of **extant life.**	**B1.** Characterize present habitability in modern environments, with a focus on resolving conditions and processes that enhance or diminish habitability.
	B2. Assess the potential of specific diagenetic conditions and processes to affect the preservation and/or degradation of signatures of extant life.
	B3. Determine if biosignatures of an extant ecosystem are present.

The search for evidence of past or extant life is a key driver of the Mars Exploration Program. The general notion that Earth and Mars may have been relatively similar worlds during their early histories, combined with the relatively early emergence of life on Earth, has led to speculation about the possibility of life on Mars. Current and emerging technologies would enable us to evaluate this possibility with scientific rigor.

The implications of a positive detection would be far-reaching. Finding life on another world would have great social and scientific impacts, and would undoubtedly motivate a variety of follow-up inquiries to understand how that life functioned or functions; which attributes of structure, biochemistry, and physiology are shared with terrestrial life; what mechanisms underlie those attributes that differ; and whether Mars preserves evidence relating to the origin of that life. An apparent negative result (noting that it is not possible to demonstrate definitively that life *did not* take hold on Mars) would also be important in the context of understanding life as an emergent feature of planetary systems. If mission analyses yield no definite evidence of life in environments that were likely capable of both supporting and preserving evidence of life, then it would become important to understand whether such absence could be understood in terms of the nature, extent, and duration of planetary and environmental conditions that may or may not have supported the origin and proliferation of life.

Presumably, the search for life would ultimately take the form of dedicated life-detection missions. Such an effort should be targeted and informed by past, ongoing, and future missions – both landed and orbital – that offer global and local perspectives on which environments may have been most suitable for hosting and preserving evidence of life. The purpose of this document is to refine such a strategy.

Challenges Inherent in a Search for Extraterrestrial Life: The Need for a Working Model

Any effort to search for life beyond Earth must confront the potential for bias and "tunnel vision" that arises from having only terrestrial life and processes on which to base our concepts of habitability, biosignatures, and biosignature preservation. Efforts should accommodate the possibility for exotic organisms that may differ in biochemistry, morphology or ecology. Conceiving life, habitability, and biosignatures in general terms will support these efforts. Nonetheless, a working concept of life must be adopted in order to define what measurements should be made in targeting and executing a search for evidence of life.

It is difficult (and perhaps not presently possible) to define life, but for the purposes of formulating a search strategy, it is largely suitable to simply consider life's apparent properties – what it needs, what it does, and what it is made of. To this end, the NRC Committee on an Astrobiology Strategy for the Exploration of Mars (Jakosky, 2007) assumed that hypothetical Martian life forms would exhibit the following characteristics (quoting verbatim):

- They are based on carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and the bio-essential metals of terrestrial life.
- They require water.
- They have structures reminiscent of terran [Earth-based] microbes. That is, they exist in the form of self-contained, cell-like entities rather than as, say, a naked soup of genetic material or freestanding chemicals that allow an extended system (e.g., a pond or lake) to be considered a single living system.
- They have sizes, shapes and gross metabolic characteristics that are determined by the same physical, chemical, and thermodynamic factors that dictate the corresponding features of terran organisms. For example, metabolic processes based on the utilization of redox reactions seem highly plausible. But the details of the specific reactions, including the identities of electron donors and electron acceptors, will be driven by local conditions and may well not resemble those of their terran counterparts.
- They employ complex organic molecules in biochemical roles (e.g., structural compounds, catalysis, and the preservation and transfer of genetic information) analogous to those of terran life, but the relevant molecules playing these roles are likely different from those in their terran counterparts.

This set of characteristics is adopted here as a working basis for developing an approach to characterizing habitability and seeking biosignatures on Mars. Importantly, the specifics of this model impact not only what features would be considered biosignatures, but also our perception of what specific conditions and processes would determine habitability and preservation potential.

Delineating Objectives: Past versus Extant Life

Finding evidence of *either* past or extant life on Mars would be a watershed event. However, significant differences exist in the strategies, technologies, target environments, and forms of evidence that would be most appropriate in searching for ancient versus extant life. For example, it is generally thought that definitive evidence of life in ancient samples might only be obtained through return of samples from Mars to Earth, whereas some investigations for extant life might be best, or obligately, conducted *in situ*. For this reason, separate objectives are delineated for ancient and extant life (Objectives A and B, respectively), with associated investigations that are specifically tailored to each search type. A clear scientific strategy (i.e., an investigative plan built on target-specific hypotheses and measurements) can only be formulated once an environmental record or environment is understood in sufficient detail. Ancient systems are given higher priority here because observations made by previous missions have identified a range of surface to near surface (top few meters) environments that have preliminary indicators of prior habitability, conditions that could preserve ancient biosignatures, and geologic context, which collectively support clear strategies for searching for evidence of life within those targets. In contrast, such observations have not yet yielded the level of environmental detail necessary to identify clear targets and associated strategies in a search for extant life. However, the order of priority should remain open to reversal based on new observations that provide evidence of targets that could host extant life, and the delineation of clear strategies for seeking evidence of that life.

Delineating Investigations: Habitability, Preservation Potential, and Biosignatures

Mars presents a diverse array of environments that may vary widely in the type, abundance, and quality of biosignature evidence they could or do preserve. Thus, missions that search for evidence of life should be strongly informed by assessment of (a) the nature and extent of habitability for a given environment, i.e., what conditions and processes that define the environment are supportive or obstructive to life and over what timescales? and (b) biosignature preservation potential, i.e., what conditions and processes during deposition, diagenesis, burial, and exhumation enhance preservation or hasten degradation of different types of biosignatures? The structure of Objectives A and B below reflects this notion, with separate sub-objectives for characterizing habitability and preservation potential that would serve as precursors to the life-detection sub-objective. Within the context of Objectives A and B, the chief purpose of the habitability and preservation potential sub-objectives would be to enhance the likelihood of successful biosignature detection, and they should be conducted in this spirit, rather than as ends to themselves. The prerequisite nature of Objectives A and B should be considered in reference to the body of information provided by the Mars exploration program overall, rather than as a necessarily mission-specific requirement. That is, individual missions may not require an onboard capability to extensively address Objectives A and B if previous or ongoing missions provide the insights into habitability and preservation potential needed to inform targeting, sample selection, and measurement strategy.

The concepts of habitability, preservation potential, and biosignatures, as they bear on Goal I and Mars exploration, are discussed in detail in the appendix. Key considerations are as follows:

Habitability: In the context of Mars exploration, "habitability" has previously been defined as the potential of an environment (past or present) to support life of any kind, and has been assessed largely in reference to the presence or absence of liquid water. To support site selection for life-detection missions, additional metrics should be developed for resolving habitability as a continuum (i.e., more habitable, less habitable, uninhabitable) rather than a one-or-zero function, and this would require that additional determinants of habitability be characterized. Based on the working model above, the principal determinants of habitability for life on Mars would be: the presence, persistence, and chemical activity of liquid water; the presence of thermodynamic disequilibria (i.e., suitable energy sources); physicochemical environmental factors (e.g., temperature, pH, salinity, radiation) that bear on the stability of covalent and hydrogen bonds in biomolecules; and the presence of bioessential elements, principally C, H, N, O, P, S, and a variety of metals. An expanded discussion of the bearing of these factors on habitability is included in Appendix 3.

Preservation Potential: Once an organism or community of organisms dies, its imprint on the environment begins to fade. Understanding the processes of alteration and preservation related to a given environment, and for specific types of biosignatures, is therefore essential. This is true not only in the search for fossil traces of life, but also for extant life. For example, metabolic end products that are detected at a distance, in time and space, from their source, may be subject to some level of alteration or dilution. Degradation and/or preservation of physical, biogeochemical and isotopic biosignatures is controlled by a combination of biological, chemical and physical factors, and a combination that would best preserve one class of features may not be favorable for another. Some of these factors are familiar since they occur on Earth, e.g., aqueous, thermal, and barometric diagenesis, chemical and biological oxidation, physical destruction by mechanical fragmentation, abrasion, and dissolution, protection by minerals (i.e., inclusions, surface bonding, grain boundaries), etc. Other factors pertinent to preserving biosignatures in Martian geological materials, but poorly understood in the absence of sufficient terrestrial analogs, are timing and cumulative exposure to ionizing radiation as well as impact shock and heating. All of these factors might have varied substantially over time and from one potential landing site to the next, even among sites that had been habitable at some time in the past. *Characterization of the environmental conditions and processes on Mars during deposition, diagenesis, burial, and exhumation that enhance preservation of specific biosignature types is a critical prerequisite in the search for life.* Accordingly, both the selection of landing sites and where/what materials will be acquired for measurements (e.g. sample depth, exposure age, cave wall/floor) should take into consideration the capacity for biosignatures to have been preserved. Further discussion of preservation potential may be found in the Appendix.

Biosignatures: Biosignatures can be broadly organized into three categories: physical, biomolecular, and metabolic. Physical features range from individual cells to communities of cells (colonies, biofilms, mats) and their fossilized counterparts (mineral-replaced and/or organically preserved remains) with a corresponding range in spatial and temporal scale. Molecular biosignatures relate to the structural, functional, and information-carrying molecules that characterize life forms. Metabolic biosignatures comprise the unique imprints upon the environment of the processes by which life extracts energy and chemical resources to sustain itself – e.g., rapid catalysis of otherwise sluggish reactions, isotopic discrimination, biominerals, and enrichment or depletion of specific elements. Significantly, examples can be found of abiotic features or processes that bear similarity to biological features in each of these categories. However, biologically mediated processes are distinguished by speed, selectivity, and a capability to invest energy into the catalysis of unfavorable processes or the handling of information. It is the imprint of these unique attributes that resolves clearly biogenic features within each of the three categories. Importantly, biosignature concentration varies significantly among environments and depends on ecosytem productivity (largely a function of the factors that determine habitability) and the nature of deposition. Identification of environments that potentially concentrate biosignatures, or particular types of biosignatures, would aid site selection. A detailed discussion of biosignatures appears in the Appendix.

Ordering and Prioritization

Objectives are listed in priority order, based on the rationale outlined above (see "***Delineating objectives…***"). Within Objectives A and B, Sub-objectives 1 and 2 need to be addressed prior to Sub-objective 3, based on the rationale outlined above (see "***Delineating investigations…***"). More specifically, the habitability sub-objectives (A1 and B1) and preservation potential sub-objectives (A2 and B2) are considered prerequisite "screening" to support the life detection objectives (A3 and B3). The life detection sub-objective has the overall highest priority within each objective. Priority is implied in the ordering of investigations within Objectives A and B. However, it should be noted that a sub-objective would not be "complete" without the conduct of each investigation. In this case, priority implies a sense of which investigations would yield the greatest "partial progress" with respect to a given sub-objective.

Objective A: Determine if paleoenvironments having high combined potential for prior habitability and biodsignature preservation record evidence of past life.

Sub-objective A1: Characterize the prior habitability of paleoenvironments, with a focus on resolving former conditions and processes that influence the degree or nature of habitability in each paleoenvironment.

Investigations are focused on establishing overall geological context and constraining each of the factors thought to influence habitability. Importantly, it must be noted that the purpose of such investigations is to constrain *ancient* conditions by inference, based on the presently available record of such conditions. Data relevant to each investigation could be obtained by a variety of methods including orbital measurements – for example, by characterizing morphology and mineralogy in concert. Such measurements should be heavily utilized as a screening tool with which to target landed platforms capable of more detailed measurements.

Investigation A1.1: Establish overall geological context.

Investigation A1.2: Constrain prior water availability with respect to duration, extent, and chemical activity.

Investigation A1.3: Constrain prior energy availability with respect to type (e.g., light, specific redox couples), chemical potential (e.g., Gibbs energy yield), and flux.

Investigation A1.4: Constrain prior physicochemical environment, emphasizing temperature, pH, water activity, and chemical composition.

Investigation A1.5: Constrain the abundance and characterize potential sources of bioessential elements.

Sub-objective A2: Assess the potential of conditions and processes to have influenced preservation or degradation of biosignatures and evidence of habitability, from deposition to time of observation. Identify specific paleoenvironmental deposits and subsequent

geological conditions that have high potential to have preserved evidence of individual or multiple types of biosignatures.

Investigation A2.1: Identify conditions and processes that aided preservation and/or degradation of complex organic compounds, focusing particularly on characterizing: redox changes and rates in surface and near-surface environments (including determination of the "burial depth" in regolith or rocks that may shield from ionizing radiation effects); the prevalence, extent, and type of metamorphism; and potential processes that influence isotopic or stereochemical information.

Investigation A2.2: Identify the conditions and processes that aided preservation and/or degradation of physical structures on micron to meter scales.

Investigation A2.3: Characterize the conditions and processes that aided preservation and/or degradation of environmental imprints of metabolism, including blurring of chemical or mineralogical gradients and changes to stable isotopic composition and/or stereochemical configuration.

Sub-objective A3: Determine if ancient biosignatures are present.

Investigation A3.1: Characterize organic chemistry, including (where possible) stable isotopic composition and stereochemical configuration. Characterize co-occurring concentrations of possible bioessential elements.

Investigation A3.2: Test for the presence of possibly biogenic physical structures, from microscopic (micron-scale) to macroscopic (meter-scale), combining morphological, mineralogical, and chemical information where possible.

Investigation A3.3: Test for the presence of the prior metabolic activity, including: stable isotopic composition of possible metabolic reactants and products (i.e. metabolites); mineral or other indicators of prior chemical gradients; localized concentrations or depletions of potential metabolites (e.g. biominerals); and evidence of catalysis in chemically sluggish systems.

Objective B: Determine if localities having high combined potential for modern habitability and biosignature presence host evidence of extant life.

Sub-objective B1: Characterize present habitability in modern environments, with a focus on resolving conditions and processes that enhance or diminish habitability.

Investigations are built on the assumption that, because liquid water is not presently stable at the surface of Mars, any modern habitable environments would be in the near- to deep subsurface (>1 meter). Investigations are focused (and priorities based) on the information needed to fully characterize habitability in such environments without reference to the present ability or difficulty in obtaining such information. The purpose of this approach is to accommodate potential future missions and technologies that might enable direct measurements to be made by virtue of direct access to the subsurface. However, orbital platforms might be capable of providing some information in each category, either by direct measurement (e.g., radar sounding to search for possible aquifers) or by inference (e.g., trace gas emissions that may imply a source region having liquid water and well constrained redox conditions). Significant use should be made of such orbital measurements in providing global screening-level constraints on subsurface habitability.

Investigation B1.1: Identify areas where liquid water (including brines) presently exists, with emphasis on reservoirs that are relatively extensive in space and time.

Investigation B1.2: Identify areas where liquid water (including brines) may have existed at or near the surface in the relatively recent past including periods of significant different obliquity.

Investigation B1.3: Establish general geological context (e.g., rock-hosted aquifer or sub-ice reservoir; host rock type).

Investigation B1.4: Identify and constrain the magnitude of possible energy sources (e.g., water-rock reactions, ionizing and non-ionizing radiation) associated with occurrences of liquid water.

Investigation B1.5: Assess the variation through time of physical and chemical conditions, (particularly temperature, pH, and fluid composition) in such environments and potential processes responsible for observed variations.

Investigation B1.6: Identify possible supplies of bioessential elements to these environments.

Sub-objective B2: Assess the potential of specific diagenetic conditions and processes to affect the preservation and/or degradation of signatures of extant life.

Investigation B2.1: Evaluate the physicochemical conditions and processes of surface regolith or rock environments in terms of their potential for preserving or degrading biosignatures, and the effects of these conditions and processes on specific types of potential biosignatures.

Investigation B2.2: Evaluate the potential rate of physical degradation from wind abrasion, dust storms, dust devils, and frost action.

Investigation B2.3: Evaluate the physicochemical conditions and processes at depth in regolith, ice, or rock environments in terms of their potential for preserving or degrading biosignatures.

Sub-objective B3: Determine if biosignatures of an extant ecosystem are present.

Investigation B3.1: Test for the presence of ongoing metabolism, in the form of rapid catalysis of chemically sluggish reactions, stable isotopic fractionation, and/or strong chemical gradients, or potential biogenic gases, which could migrate from habitable deep subsurface environments to surface environments.

Investigation B3.2: Characterize organic chemistry and co-occurring concentrations of bioessential elements, including stable isotopic composition and stereochemistry. Analyses might include but should not be limited to known molecular markers of terrestrial life, such as membrane lipids, proteins, nucleic acid polymers, and complex carbohydrates.

Investigation B3.3: Test for the presence of organic and mineral structures or assemblages that might be associated with life. Seek evidence of mineral transformations bearing evidence of biological catalysis (e.g., depletion of possibly bio-essential elements in mineral surfaces).

GOAL II: UNDERSTAND THE PROCESSES AND HISTORY OF CLIMATE ON MARS

Objectives	Sub-Objectives
A. Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration.	**A1.** Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal and multi-annual timescales.
	A2. Constrain the processes that control the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment.
	A3. Constrain the processes that control the chemical composition of the atmosphere and surrounding plasma environment.
	A4. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.
B. Characterize the history of Mars' climate in the recent past, and the underlying processes, under different orbital configurations.	**B1.** Determine how the chemical composition and mass of the atmosphere has changed in the recent past.
	B2. Determine the record of the recent past that is expressed in geological features of the polar regions.
	B3. Determine the record of the climate of the recent past that is expressed in geological features of low- and mid-latitudes.
C. Characterize Mars' ancient climate and underlying processes.	**C1.** Determine present escape rates of key species and constrain the processes that control them.
	C2. Find physical and chemical records of past climates and factors that affect climate.
	C3. Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.

The fundamental scientific questions that underlie the Mars Climate Goal concern how the climate of Mars has evolved over time to reach its current state, and the processes that have operated to produce this evolution.

Mars climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile reservoirs evaluated from diurnal to geologic time scales. The climate history of Mars can be divided into three distinct epochs: (i) Present climate, operating under the current obliquity; (ii) Climate of the geologically recent past, operating under similar pressures, temperatures, and composition, but over a range of orbital variations (primarily obliquity); and (iii) Ancient climate, when the pressure and temperature may have been substantially higher than at present, the atmospheric composition may have been different, and liquid water may have been stable on the surface.

The Climate Goal is organized around three objectives, each pertaining to the different climate epochs. Objectives are given in priority order, consistent with the philosophy that the present is the key to the past. Investigations are assigned a prioritization: high, medium, or low. This prioritization is based on subjective weighting that includes consideration of existing measurements with respect to needed measurements, relative impact of an investigation towards achieving an objective, and identification of investigations with logical prerequisites. Importantly, the investigation prioritization is only with respect to the Investigations within the parent Sub-objective. Thus, it is possible that a high priority investigation in lower priority Objective C could be on par with or more important than a lower priority investigation in the higher priority Objective B.

On Mars, the present holds the key to the past: a comprehensive understanding of the fundamental processes at work in the present climate is necessary to have confidence in conclusions reached about the recent past and ancient climate, when Mars may have been more habitable than today. Since many of the processes that governed the climate of the recent past are likely similar to those that are important today, an understanding of the present climate must be firmly established before an understanding of the climate of the recent past can be developed. Numerical models play a critical role in interpreting the recent past and ancient climate, and it is imperative that they be validated against the present climate in order to provide confidence in results for more ancient climates that are no longer directly observable.

Objective A: Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration

Our understanding of the chemistry, dynamics, and energetics of the present Martian atmosphere forms the basis for understanding the recent past and ancient climate. The atmosphere system consists of many coupled subsystems, including surface and near-surface reservoirs of CO_2, H_2O and dust, the lower atmosphere, the upper atmosphere, and the surrounding plasma environment. Each of these regions is an integral part of the interconnected atmospheric system, yet different processes dominate in different regions. Well-planned measurements of all of these regions enable characterization of the physical processes that maintains and drives the present climate of Mars.

This Objective will not be achieved by observations alone. Numerical modeling of the atmosphere provides an additional, critical element to understanding atmospheric and climate processes. Models provide full dimensional and temporal context to necessarily sparse and disparate observational datasets, and models provide a virtual laboratory for testing whether observed or inferred conditions are consistent with proposed processes. Proper consideration of this essential modeling element should be given to any proposed experiment.

Sub-Objective A1: Constrain the processes that control the present distributions of dust, water, and carbon dioxide in the lower atmosphere, at daily, seasonal and multi-annual timescales.

Knowledge of the processes controlling distributions of dust, water and CO_2 may be arrived at by direct measurement of these substances, and by measurement of atmospheric state, circulation and forcings in the atmosphere. Although tremendous advances have been made towards characterizing and quantifying the atmosphere, existing measurements of the spatial and temporal distributions of dust, water and carbon dioxide, and the atmospheric state in the lower atmosphere are inadequate to achieve this sub-objective. A comprehensive and consistent picture of the relevant atmospheric processes will be achieved primarily through direct measurement of atmospheric forcing (e.g., radiation, turbulent fluxes), the quantities that feed into that forcing (e.g., dust and clouds), and the response of the atmosphere (e.g., temperature, pressure, winds) to the forcing.

Obtaining a quality data set from a properly accommodated weather station (i.e., one in which thermal and mechanical contamination for the spacecraft is minimal) is of highest priority. In nearly half a decade of attempts, there has yet to be an in situ weather station investigation that has successfully and simultaneously measured, without substantial spacecraft contamination or operational issues, the basic meteorological parameters of pressure, temperature, and wind. Any proposed measurement of in situ meteorological parameters should demonstrably show the impact of accommodation on the fidelity of the measurements. Once quality surface measurements of basic meteorological parameters have been acquired, measurements of quantities that have been poorly or never measured should generally be given higher priority.

In addition to a single surface station, in situ measurements can be obtained by networked landed observatories or aerial platforms (e.g., balloons, airplanes). Each of these platforms provides unique measurements helpful to a complete understanding of the climate system. Regardless of platform, in situ measurements also provide calibration and validation for complementary measurements retrieved from orbit, and provide data critical to the validation of climate and weather models. The importance of data for these purposes should be appropriately recognized and valued in any proposed experiment.

Substantial progress on this sub-objective has been made via remote sensing, particularly from orbit. Retrievals of atmospheric temperature profiles from MGS now provide a good climatological record of global scale column dust, water and ice opacity. MCS has revealed a vertical dust structure more complex than previously thought. The bulk, global thermal structure has also been captured over multiple years. Still, these orbital measurements are substantially limited in their local time coverage and over the cold poles. Moreover, nadir measurements have generally been limited to vertical resolutions of about a scale height, while off-nadir or limb sounding measurements have generally been limited to horizontal resolutions on the order of 200 km. Future progress will be made by acquiring greater coverage over the full diurnal cycle, by improving the vertical resolution of temperature, dust, water vapor, and dust profiles. Therefore, future orbital measurements that are motivated by this Sub-Objective should significantly improve spatial and temporal coverage and resolution beyond the existing data, and they should ideally span multiple Mars years. Further, the vertical resolution of profiles must be demonstrably matched to the processes or region of interest. For example, if the focus is on the daytime convective boundary layer, a profiler must provide sufficient vertical resolution to accurately quantify the very steep superadiabatic lapse rate.

This sub-objective has substantial relevance to robotic exploration of Mars. Landing spacecraft safely on the surface of Mars requires the ability to adequately predict the structure and dynamics of the atmosphere, as well as its natural variability, at the time and place of landing. Because this atmospheric knowledge must be established well in advance of landing (often years), models that are validated and constrained by previous observations are the only tool available. Presently, the atmospheric models used to make these predictions are poorly constrained, especially at the local- and lander-scale, by observations. An efficient mechanism for reducing risk would be to reduce large uncertainties in atmospheric predictions by acquiring suitable observations as constraints, which would correspondingly reduce engineering margins in spacecraft design. Generally, achieving this Sub-objective will significantly fill knowledge gaps for entry, descent and landing operations, which benefits the entire Mars Exploration Program, and facilitates achievement of every MEPAG Science goal.

Investigation A1.1: Measure the state and variability of the lower atmosphere from turbulent scales to global scales (High Priority).

This investigation focuses on the state or response of the atmosphere to forcing. Dust, water and CO_2 distributions vary on daily, seasonal, inter-annual, and perhaps longer timescales and on all spatial scales from turbulent scales to global scales. This range of scales necessitates a range of investigational approaches:

- *Turbulent (microscale) scale: Basic measurements of pressure(p), temperature(T), wind(V), and water(RH), together with the measurement of turbulent fluxes of heat, momentum at a variety of sites at different seasons.*
- *Mesoscale: Measurement of atmospheric properties (p, T, V, RH), to quantify the role of physiographic forcing in local/regional circulations, gravity waves and tracer transport; Quantify mesoscale circulations, including slope flows, katabatic winds and convergence boundaries.*
- *Global scale: Measurement of atmospheric properties to quantify the mean, wave and instantaneous global circulation patterns, and the role of these circulations in tracer (e.g., dust/water) transport; quantify CO_2 cycle and global climate change (e.g., secular pressure changes).*

Previous experiments have provided some, but not all, of the data central to this investigation, with varying degrees of success and fidelity. Wind measurements have been particularly troublesome, and quality wind measurements at the surface, made simultaneously with temperature and pressure, remain a high priority. New and novel measurements are generally considered as higher priority than those which duplicate or refine existing data. For example, a landed meteorological payload that measures only temperature and pressure is helpful, but the additional measurement of winds and turbulent fluxes, would be new and more likely to make a substantial rather than incremental advance in knowledge.

Regional (mesoscale) circulations forced most strongly by topography are thought to strongly control the atmosphere near the surface and may play an important role in the transport of dust, water and other species. Topography is also likely to trigger large amplitude gravity waves that can redistribute momentum in the vertical and produce regions that are favorable for cloud condensation. Experiments that measure fundamental parameters (e.g., p, T, V, RH) and connect these parameters to distributions of dust and water, both at the surface and in the vertical, are necessary to characterize the nature of the atmosphere at the mesoscale. Because the mesoscale environment is so strongly coupled to topography, measurements at locations that represent the diversity of Martian geography are required (e.g., plains, craters, valleys).

Meteorological observations gathered on daily- to decade-long timescales establish the magnitude of inter-annual variability, characterize larger-scale circulations (e.g., baroclinic eddies and the thermal tide), and aid in the determination of the magnitude of any long-term trends in the present climate system. Specifically, these measurements provide a means to characterize the annual variations and cycling of volatiles, condensates, and dust. Measurement of noncondensables (e.g., N_2, Ar, CO) can also provide important information on the global transport and cycling of mass. These observations of the present climate would also assist in identifying the causes of the north/south asymmetry in the nature of the polar caps, and the physical characteristics of the layered deposits, which are important for studies of the climate of the recent past.

Investigation A1.2: Characterize dust, water vapor, and clouds in the lower atmosphere (High Priority).

Dust and clouds are strong, radiatively active constituents of the atmosphere, and their distribution is tied directly to transport processes. Previous and ongoing measurements from orbit have provided a multi-year climatology of column dust, water vapor and cloud, although it is problematic over the poles and is based on a narrow window of local times. The vertical distribution is less well characterized. MCS has demonstrated that the vertical distribution of dust can be complex and the processes leading to the complex distributions are uncertain. Vertical water vapor distributions are relatively unknown, but probably exhibit similar complex structures. Knowing the distribution of aerosols and vapor is still not enough. The radiative forcing is a function of the optical properties in addition to the distribution. Characterization of dust, water vapor, and clouds may be decomposed into four areas:

- *Spatial and temporal variations in column abundance*
- *Vertical structure*
- *Physical and optical properties*
- *Electrical properties of dust*

While additional column abundance information is welcome, significantly greater knowledge gaps remain about the vertical distribution of dust and water, and how these distributions are connected to the atmospheric circulation. Similarly, the properties of atmospheric aerosol, which are critical to understanding the radiative processes, are poorly constrained. The electrical properties of dust have never been measured. This measurement has particular importance for exploration hazards (See Goal IV). It is also potentially relevant for electrochemical processes. Vertical structure and physical properties are the highest priority in this list.

Investigation A1.3: Measure the forcings that control the dynamics and thermal structure of the lower atmosphere (High Priority).

Measurement of the forcing mechanisms of the atmosphere are largely absent from the observational record. Yet, these mechanisms are crucial to understanding atmospheric processes. The forcing mechanisms are partially determined by the state of the atmosphere (e.g., the distribution of dust), but they also simultaneously act to produce the observed state of the atmosphere. The forcing mechanisms may be investigated in three ways:

- *Surface energy balance*
- *Momentum budget*
- *Atmospheric energy budget*

Quantification of the distribution of energy inputs and outputs at the surface is essential to interpreting the observed behavior of the atmosphere near the surface and in the planetary boundary layer. The surface budget is comprised of insolation, reflected light, incoming and outgoing infrared radiation, turbulent fluxes, energy conducted to/from the surface, and possibly condensational processes. The surface energy balance is a high priority within this investigation.

Wind/momentum measurements in the atmosphere other than at the surface are completely absent. This is a major hindrance to achieving this investigation and the sub-objective. The atmospheric momentum fields have been diagnosed from the thermal structure assuming dynamical balance. However, the diagnostics are extremely sensitive to the temperature field, and the technique completely fails in the tropics. Numerical models attempt to characterize the momentum fields, but the errors in the model thermal fields compared to existing observations raise concerns about the fidelity of the model results. Measurement of winds is a high priority within this investigation.

The magnitude and partitioning of energy in the free atmosphere (above the PBL) is the major driver of atmospheric circulations. Knowledge of the spatial variability of deposition of solar radiation and absorption/emission of IR radiation ties the radiative forcing processes to the observed thermal and kinematic state of the atmosphere. While this information is important, it is of lesser priority than the other two areas.

Sub-objective A2: Constrain the processes that control the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment.

Knowledge of spatial and temporal variations in the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment is not yet sufficient to determine how momentum and energy are distributed throughout the atmosphere system.

In the upper atmosphere, both neutral and ionized species are present. Both influence the behavior of the atmosphere system. The dynamics and energetics of neutrals and plasma in the upper atmosphere are influenced through coupling to the lower atmosphere and by interactions with the solar wind. Consequently, solar cycle variations are expected to be significant. The forcings and responses relevant to the dynamics and energetics of the upper atmosphere and surrounding plasma environment have hardly been constrained by observations. Crustal magnetic fields are likely to lead to significant geographical variations in the dynamics and energetics of plasma, and potentially also the neutral thermosphere via ion-neutral interactions.

This sub-objective will require measurements of the densities, velocities, and temperatures of neutral and ionized species in the upper atmosphere, as well as measurements of the dominant forcings (solar irradiance, coupling to the lower atmosphere, conditions in the solar wind and magnetosphere). The MAVEN mission is likely to produce substantial contributions towards this sub-objective, and the priority ratings of the investigations reflect the expectation that MAVEN will successfully complete its prime mission objectives. If those objectives should not be met, then Investigations A.2.1, A.2.3 and A.2.4 would become high priority. Investigation A.2.2 remains a relatively low priority within this sub-objective, regardless of MAVEN.

<u>Investigation A2.1:</u> Measure the spatial distribution of aerosols, neutral species, and ionized species in the upper atmosphere (Medium Priority).

The constituents of the upper atmosphere include aerosols, neutral species, and ionized species. Due to their radiative properties, aerosols can markedly affect temperatures, and hence density distributions. The atmosphere is predominantly neutral at the base of the upper atmosphere, but becomes increasingly ionized as altitude increases. Since ionized species in the upper atmosphere are generally derived from neutrals, the behaviors of neutrals and ions are tightly linked. Thus, the three major categories for investigation are:

- *Aerosols*
- *Densities of major neutral species*
- *Densities of electrons and major ions*

Observations by SPICAM have established that aerosols, specifically CO_2 ice, can be present in the upper atmosphere. It is also possible that dust may be lofted towards the base of the upper atmosphere. There are strong seasonal and spatial variations in the abundances of aerosols in the upper atmosphere. Variability with local time is not well-constrained.

Prior to the arrival of MAVEN, there have been few measurements of the densities of major neutral species in the upper atmosphere. The neutral density distribution in the upper atmosphere sets the stage for the production of the ionosphere and exosphere, both of which play crucial roles in atmospheric evolution, as well as in coupling to the magnetosphere/solar wind.

Electron densities in the upper atmosphere have been measured frequently by radio occultation instruments, yet these data cover only a limited range of local times. They have also been measured extensively by the MARSIS radar, albeit with less accuracy and lower vertical resolution than the radio occultation observations. Available electron density measurements over strongly magnetized regions suggest very complex spatial distributions of densities that have yet to be comprehensively explored.

Investigation A2.2: Measure velocities of neutral and ionized species in the upper atmosphere (Low Priority).

The dynamics of the upper atmosphere are essentially unobserved. Neutral winds influence the thermal structure of the upper atmosphere and the transport of plasma. The transport of plasma will essentially control plasma densities throughout much of the ionosphere. Differential motions of ions and electrons generate currents, which are an important factor in the exchange of momentum and energy between the thermosphere/ionosphere and the magnetosphere above. There are two measurements of concern:

- *Neutral wind*
- *Velocities of electrons and major ions*

There have been no direct measurements of the velocities of neutral and ionized species in the upper atmosphere. Some constraints on the neutral wind have been provided by nightside airglow observations of the recombination of species photo-produced on the dayside, but these have poor accuracy and spatial resolution. The upper atmospheric circulation is predicted to be integrated with the circulation of the lower atmosphere, which makes the upper atmospheric circulation a valuable diagnostic of how the lower and upper atmospheres are coupled.

There have been no direct or indirect measurements of the velocities of electrons or ions in the upper atmosphere. In certain regions, transport processes are exceedingly important for shaping the distribution of ionospheric densities. In others, they play a negligible role. Velocity measurements would enable determination of where transport matters. Velocities are also important via their influence on ionospheric currents and associated electrodynamics.

Investigation A2.3: Measure temperatures of neutral and ionized species in the upper atmosphere (Medium Priority).

The Martian upper atmosphere thermal structure is poorly constrained by a limited number of measurements at selected locations, seasons, and periods scattered throughout the solar cycle. Temperatures of ions and electrons have scarcely been measured. Yet temperatures are the primary expression of the heating and cooling processes by which energy passes through the upper atmosphere. In turn, temperature gradients drive atmospheric motions and affect ionospheric reaction rates. The measurements of concern are:

- *Neutral temperature*
- *Temperatures of electrons and major ions*

Temperatures vary greatly with altitude, increasing sharply from the cold mesopause as they asymptotically approach the hot exospheric value. Since temperatures are controlled by the solar EUV input, they also vary seasonally due to orbital eccentricity and on longer timescales due to the solar cycle. Temperatures are affected by composition via the influence of the atomic oxygen abundance on CO_2 15 µm cooling.

In the lower portions of the ionosphere, plasma and neutrals are in thermal equilibrium and electron and ion temperatures match the temperature of the much more abundant neutrals. As altitude increases, electron and ion temperatures become decoupled from, and much greater than, the neutral temperature. The electron temperatures influence the rates of many critical ionospheric reactions and gradients in both ion and electron temperatures produce pressure gradient forces that drive the transport of plasma.

Investigation A2.4: Measure the forcings that control the dynamics and thermal structure of the upper atmosphere (Medium Priority).

Measurement of the forcing mechanisms of the upper atmosphere are largely absent. Yet, these mechanisms are crucial to understanding upper atmospheric processes. The forcing mechanisms are primarily imposed from outside the upper atmosphere and are minimally affected by the state of the upper atmosphere itself. They may be investigated in three ways:

- *Solar irradiance*
- *Conditions in the solar wind and magnetosphere*
- *Coupling between lower and upper atmosphere*

The amount of soft X-ray (0.1-5 nm) and EUV (5-110 nm) solar radiation most responsible for heating the upper atmosphere of Mars (and forming its ionosphere) varies significantly over time. These temporal variations result from the changing heliocentric distance (~1.38-1.67 AU), the planet's obliquity (determining the local season), and the changing solar radiation itself. Both solar rotation (~27-day periodic changes in the planet facing solar output) and solar cycle (~11-year periodic overall changes in solar output) variations of the solar X-ray and EUV fluxes are significant (up to factors of ~2 to 10).

Non-photon aspects of solar output, namely the magnetic field and thermal and energetic charged particles, also influence the state of the upper atmosphere. Their impact on the upper atmosphere is mediated by the magnetosphere. The effects of external charged particles on the upper atmosphere depends on geographic location: mini-magnetospheres produced by crustal magnetic fields will exclude external charged particles from some regions and focus them into others.

The upper atmosphere rests upon the lower atmosphere and is consequently sensitive to conditions below and disturbances propagating upwards from below. These include gravity waves, planetary waves and tides, and dust storms. Upward propagating tides and planetary waves (and their nonlinear interactions) and gravity waves deposit momentum throughout much of the upper atmosphere. During a dust storm, enhanced dust loading in the lower atmosphere heats and inflates the lower atmosphere, thereby elevating pressure levels in the upper atmosphere. The global circulation adjusts in response.

Sub-Objective A3: Constrain the processes that control the chemical composition of the atmosphere and surrounding plasma environment.

Knowledge of spatial and temporal variations in the abundance, production rates, and loss rates of key photochemical species (e.g., O_3, H_2O, CO, OH, CH_4, SO_2, the major ionospheric species) is not yet sufficient to provide a detailed understanding of the atmospheric chemistry of Mars.

Observations of atmospheric composition are scarce, both from orbit and from the surface. ESA's Trace Gas Orbiter mission would make progress in this regard. Since TGO has yet to launch, the Investigations do not assume a successful prime mission. If the MAVEN mission successfully completes its prime mission, it should make substantial contributions toward understanding the composition of the upper atmosphere and plasma environment. The investigation priorities do assume that MAVEN will achieve its prime mission objectives.

Current multi-dimensional photochemical models predict the global 3-dimensional composition of the atmosphere, but require validation of key reactions, rates, and the significance of dynamics for the transport of atmospheric constituents. It is likely that some important processes for atmospheric chemistry have yet to be identified. In the lower atmosphere,for example, recent in situ measurements of O by MSL strongly suggest an unknown or unaccounted for process is operating. Also, the importance of electro-chemical effects, which may be notably significant for certain species (e.g., H_2O_2), and of chemical interactions between the surface and the atmosphere have yet to be established. There is considerable uncertainty in the surface fluxes of major species. The curious case of Methane has yet to be fully resolved. In situ MSL measurements indicate background levels of ~1 ppb, but temporary excursions of up to ~7 ppb have been found. The MAVEN mission will make measurements of some key species in the upper atmosphere and its findings may also illuminate the chemistry of the lower atmosphere to some degree.

This sub-objective will require global orbital observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the solar cycle, seasons, and dust storms. It is anticipated that MAVEN and ESA's TGO will make substantial progress on this sub-objective.

Investigation A3.1: Map spatial and temporal variations in the column abundances of species (listed) that play important roles in atmospheric chemistry or are transport tracers (Medium Priority):

- *Non-condensable species including N_2, Ar, and CO.*
- *Other species including H_2O, OH, CO_2, O, O_2, O_3, SO_2, CH_4.*

Non-condensable species provide information on atmospheric transport. Non-condensables are species that are stable or have very long photochemical lifetimes compared to the annual CO_2 condensation cycle and which have condensation temperatures below that found on Mars. Measuring the enrichment of non-condensables directly measures the mixing of the atmosphere.

Mapping of column abundances provides information on the horizontally spatial and temporal variability of sources and sinks. By tracking species with different photochemical lifetimes, information on atmospheric transport can also be extracted.

Investigation A3.2: Measure globally the vertical profiles of key chemical species (High Priority):

- *Neutral species including H_2O, CO_2, CO, O_2, as well as isotopes of H, C and O.*
- *Ionized species including O+, O_2+, CO_2+, HCO+, NO+, CO+, N_2+, OH-.*

Measurements of the vertical profile of species couples photochemistry with vertical diffusion and mixing. Photochemical models typically predict these profiles, and measurements provide one of the most direct ways to validate and test photochemical reaction rates and pathways, and to test assumptions about vertical mixing.

Investigation A3.3: Determine the significance of heterogeneous chemical reactions (i.e., those involving atmospheric gases and solid bodies such as aerosols or surface materials) for the chemical composition of the atmosphere (Low Priority).

Heterogeneous chemistry occurs when chemical reactions are catalyzed by substrates. The substrates can be grains on the surface or aerosol in the atmosphere. The importance of heterogeneous chemistry in the Mars photochemical cycle is poorly constrained. Determining the importance is highly desirable, but better characterization of homogeneous photochemistry (Investigations A.3.1 and A.3.2) is generally considered a prerequisite to this investigation.

Investigation A.3.4: Measure key electrochemical species (Low Priority).

Electro-chemical effects may be important for production of certain species (e.g., H_2O_2) and promoting surface-atmosphere reactions, but confirmation is needed. This investigation would require global orbiter observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres, and the systematic monitoring of these atmospheric fields over multiple Mars years to capture inter-annual variability induced by the solar cycle, seasons, and dust storms.

Sub-Objective A4: Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.

Knowledge of how volatiles and dust exchange between surface, sub-surface, and atmospheric reservoirs is not yet sufficient to explain the present state of the surface and sub-surface reservoirs of water, which include buried ice, the polar caps, and the Polar Layered Deposits (PLD), and how these reservoirs influence or record the present climate.

Knowledge of the processes that control the lifting of dust from the surface and into the atmosphere are also insufficient. The most fundamental process for dust lifting is thought to be the stress exerted by the wind, and subsequent saltation of sand-sized particles that kick smaller dust particles into the air. However, rapid pressure changes associated with dust devils and electrostatic forces may also be important.

Investigation A4.1: Measure the turbulent fluxes of dust and volatiles between surface and atmospheric reservoirs (Medium Priority):

- *Turbulent fluxes as a function of surface and atmospheric properties.*
- *Dust lifting processes, including surface stress, roughness, lifting thresholds, and the distribution of sand dust.*

Wind stress is defined as the magnitude of the turbulent momentum flux in the atmospheric surface layer. Also, the intensity of dust devils has been linked to the magnitude of the turbulent heat flux. Thus, measurement of these turbulent fluxes provide a direct link to sand and dust lifting. Ideally, fluxes would be measured directly, but other methods, such as obtaining vertical profiles of winds in the surface layer, are possible.

Once the wind stress is known, there is still great uncertainty about the minimum value necessary to mobilize dust and sand, and the amount of sand/dust that is lifted once that minimum threshold value is exceeded. Simultaneous measurement the turbulent fluxes along, the properties of sand/dust on the surface and lifted into the atmosphere, and the threshold and efficiency parameters associated with that lifting are needed.

Charging of dust and sand grains due to collisions and the resulting E-fields and currents are included in this investigation. Grain charging is tied to the dust lifting and saltation process, and E-fields may play a role in dust lifting, particularly within dust devils.

Investigation A4.2: Determine how the exchange of volatiles and dust between surface and atmospheric reservoirs has affected the present distribution of surface and subsurface ice (Low Priority).

The current Martian seasonal cycle is dominated by condensation and evaporation of ~1/3 of the carbon dioxide atmosphere into the seasonal caps. Both dust and water ice are entrained in this seasonal wave and may be incorporated into more permanent icy deposits. Mechanisms of deposition (falling “snow” or direct condensation) as well as evolution and densification of deposits bear directly on the stability, evaporation, and venting of those deposits in spring.

Large-scale sub-surface water ice deposits exist at high latitudes in both hemispheres that may buffer long-term surface-atmosphere exchange. The equilibrium state between the subsurface ice and the atmosphere is unknown. Assessment of net accumulation or loss of the residual ice deposits and mass, density and volume of the seasonal ice as function of location and time are important components of this Sub-Objective. The transport of carbon dioxide may also be variable if carbon dioxide condensed in large-scale sub-surface reservoirs, such as the buried deposits discovered near the south pole by SHARAD, can exchange with the atmosphere.

Measurements that quantify the rate at which vapor diffuses between subsurface ice and the atmosphere would fall under this investigation.

Investigation A4.3: Determine how the exchange of volatiles and dust between surface and atmospheric reservoirs has affected the Polar Layered Deposits (Low Priority).

The transport of dust and water in and out of the polar regions, including the polar caps and PLD, are variable on seasonal, annual, and decadal timescales, and therefore require long-term monitoring. The PLD are thought to primarily record cyclical deposition regimes associated with changes in obliquity under the backdrop of the contemporary climate. However, the nature of these deposits at any time may also depend on the interaction of winds flowing over the ridges and troughs of the PLD. Thus, better characterization of processes now operating on the formation, removal or change in layers are germane to this investigation.

Objective B: Characterize the history of Mars' climate in the recent past, and the underlying processes, under different orbital configurations.

As the Martian obliquity varied in the geologically recent past, volatiles would have shifted between the atmosphere and reservoirs in the surface and sub-surface, thereby changing the mass of the atmosphere. It is also possible that such changes could have occurred under the current orbital configuration if carbon dioxide was exchanged between the atmosphere and the condensed reservoir discovered buried near the south pole by SHARAD. Changes in the atmospheric mass would have affected the thermal structure and dynamics of the atmosphere in myriad ways. For instance, the planetary albedo would have been different and the changed surface pressure would have altered the efficiency of dust lifting. Since CO_2 condenses under different conditions than other atmospheric species, even the atmospheric composition will have differed. Understanding Mars' climate in the recent past is necessary for interpreting many geological features from this period and for validating techniques and models used to infer the climate at even earlier times, when Mars was likely more habitable than today. The most likely location of a preserved record of recent Mars climate history is contained within the north and south polar deposits and circumpolar materials. The polar layered deposits and residual ice caps may reflect the last few hundred thousand to few million years, while terrain softening, periglacial features, and glacial deposits at mid- to equatorial-latitudes may reflect recent high obliquity cycles within the last few million years.

Understanding the climate and climate processes of Mars under orbital configurations of the geologically recent past will require interdisciplinary study of the Martian surface and atmosphere. It will also require the study of geologic materials to search for records of climates of the recent past. The Sub-Objectives described below focus on quantitative measurements of the concentrations and isotopic compositions of key gases in the atmosphere and trapped in surface materials.

Sub-objective B1: Determine how the chemical composition and mass of the atmosphere has changed in the recent past.

Knowledge of how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved over the geologically recent past to its present state is not yet sufficient to provide quantitative constraints on the evolution of atmospheric composition, on the sources and sinks of the major gas inventories, and on how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes.

The implications of this sub-objective cannot be fully understood until an adequate understanding of how atmospheric composition varies temporally and spatially in the present climate is obtained. Results from mass spectrometers on Curiosity and MAVEN are important steps towards this prerequisite. The most accessible records of the chemical composition of the atmosphere in the geologically recent past are the polar layered deposits and other gas-preserving ices, which have not been sampled by past landed missions. Knowledge of the absolute ages of analyzed samples would ensure that the results were placed in their proper context.

This sub-objective will require knowledge of the composition of the atmosphere at various times within the geologically recent past, which could be provided by high precision isotopic measurements, either in situ or on returned samples, of trapped gases in polar layered deposits or other gas-preserving ices.

<u>Investigation B1.1:</u> Measure isotopic composition of gases trapped in the Polar Layered Deposits (PLD) and near-surface ice (Medium Priority).

Sub-objective B2: Determine the record of the recent past that is expressed in geological features of the polar regions.

Knowledge of how current geological features of the polar regions have been shaped by the climate of the recent past is not yet sufficient to establish how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes.

The presence of extensive layered deposits in the polar regions suggests that the climate of Mars has undergone frequent and significant change in the geologically recent past. Clues to the evolution of the climate of the geologically recent past are recorded in the stratigraphy and physical and chemical properties of these Polar Layered Deposits (PLD). Specific examples of the type of information these deposits may preserve include a stratigraphic record of volatile mass balance; insolation; atmospheric composition; dust storm, volcanic and impact activity; cosmic dust influx; catastrophic floods; solar luminosity (extracted by comparisons with terrestrial ice cores); supernovae; and perhaps even a record of microbial life. Keys to understanding the climatic and geologic record preserved in these deposits are to determine the relative and absolute ages of the layers, their thickness, extent and continuity, and their petrological and geochemical characteristics (including both isotopic and chemical composition). Also important is to understand the processes by which they were produced.

This sub-objective will require in situ and remote sensing measurements of the stratigraphy and physical and chemical properties of the PLD.

Investigation B2.1: Map the ice and dust layers of the Polar Layered Deposits (PLD) and determine the absolute ages of the layers (Medium Priority).

Sub-objective B3: Determine the record of the climate of the recent past that is expressed in geological features of low- and mid-latitudes

Knowledge of how current geological features of low- and mid-latitudes have been shaped by the climate of the recent past is not yet sufficient to establish how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes.

High resolution orbital imaging has shown numerous examples of terrain softening and flow-like features on the slopes of the Tharsis volcanoes and in other lower-latitude regions. These features, interpreted to be glacial and peri-glacial in origin, may be related to ground ice accumulation in past obliquity extremes. The ages of these features and the conditions under which they formed provide constraints for the climate of the geologically recent past. These features are also relevant for the present climate as indicators of potential reservoirs of ice.

This sub-objective will require the identification of the ages of these features and, via modelling, determination of the range of climatic conditions in which they could have formed.

Investigation B3.1: Identify and map the location and extent of glacial and peri-glacial features and quantify the depth to any remnant glacial ice (Medium Priority).

Objective C: Characterize Mars' ancient climate and underlying processes.

There is strong evidence that the ancient climate of Mars was both very different from the present climate and more habitable than today. Yet atmospheric models are unable to reproduce and maintain the climatic conditions required to explain geomorphological and geochemical evidence for persistent liquid water. Understanding Mars' ancient climate is necessary for establishing whether habitable conditions ever occurred on Mars and, if they did, where and when.

Understanding the ancient climate and climate processes on Mars will require interdisciplinary study of the Martian surface and atmosphere. However, there is great uncertainty about the composition and state (pressures and temperatures) of the ancient atmosphere, key boundary conditions such as the topography, the abundance of dust, and the magnetic field, and the ability of the atmosphere to sustain liquid water at the surface. Atmospheric and geologic constraints must be used synergistically to develop a self-consistent picture of the ancient climate and climate evolution of Mars. In the atmosphere, understanding loss processes enables extrapolation of the state of the atmosphere, including its mass and composition, backwards in time. This provides understanding of how the ancient climate has evolved into the present climate. At the surface, observations of present geomorphology and geochemistry provide records of this evolution.

All the information collected on the ancient climate must be pulled together to produce a consistent story of paleoclimate and climate evolution. Climate models play a critical role in this endeavor. Models require as initial conditions the state and composition of the atmosphere as well as boundary conditions such as topography and water and ice reservoirs. The models rely on physical parameterizations should be tested, where appropriate, against similar processes occurring on Mars now.

Sub-objective C1: Determine present escape rates of key species and constrain the processes that control them.

Knowledge of present escape rates and processes is not yet sufficient to meaningfully constrain how the ancient atmosphere of Mars evolved into the present atmosphere.

One pathway towards determining the mass, composition, and climate of the ancient atmosphere of Mars is to start from the present atmosphere and wind back the clock. Since loss to space has been a major factor in atmospheric evolution, detailed knowledge of present escape processes will enable estimates of the nature of the ancient atmosphere. Escape rates are likely to vary spatially (e.g., due to crustal magnetic fields), seasonally (e.g., due to the water cycle and dust storms), and over the solar cycle. A multitude of processes operate to cause atmospheric loss. The systematic monitoring over multiple Mars years of escaping species, the upper atmospheric reservoir from which they are liberated, and the forcings that drive escape processes would be needed to capture the inter-annual variability induced by the solar cycle, seasons, and dust storms. These measurements would provide crucial constraints to atmospheric evolution models that extrapolate from the present atmosphere to the ancient past.

This sub-objective will require global orbital observations of neutral and plasma species, temperatures, and winds in the extended upper atmosphere, as well as complementary observations of the state of the solar wind, magnetosphere, and magnetic field, which strongly influence escape processes. It is anticipated that MAVEN will make substantial progress on this sub-objective. If successfully addressed by MAVEN, the investigations in this sub-objective should be considered of lower priority than those in other sub-objectives.

Investigation C1.1: Measure spatial and temporal variations in the escape rates of key species (High Priority).

The evolution of the climate and habitability of Mars by the escape of atmospheric species to space is of the utmost importance for scientific understanding of the planet. Escape proceeds by many different pathways that involve the neutral and plasma components of the upper atmosphere. The relative importances of these diverse pathways are not well-understood. Significant spatial and temporal variations in the escape flux associated with each escape process are anticipated: spatial due to the influence of the electromagnetic fields imposed by the interaction of the solar wind and of crustal magnetic fields, and temporal due to the importance of time-variable upper atmospheric conditions and solar forcing.

Investigation C1.2: Measure the forcings that drive escape processes (Medium Priority).

Measurement of the forcing mechanisms that drive escape processes are largely absent. Yet, knowledge of these forcings is critical to understanding atmospheric escape. These forcings may be divided into three main categories:

- *Solar irradiance,*
- *Conditions in the solar wind and magnetosphere,*

- *Coupling between lower and upper atmosphere.*

Highly time-variable soft X-ray (0.1-5 nm) and EUV (5-110 nm) solar radiation strongly influence the state of the reservoir from which escape occurs: the neutrals and ions of the upper atmosphere. Also, this solar radiation is the driving force for photochemical loss processes, One such process is the dissociative recombination of an ion and electron, which accelerates neutral fragments above the escape velocity.

Once ionized, several processes can transfer energy from the solar wind to planetary ions, and lead to heating, acceleration, and escape. These include ion pickup and sputtering, solar energetic particle-driven escape, ion bulk escape, and ion outflow. The escape fluxes associated with each of these processes will depend upon conditions in the solar wind and magnetosphere.

The upper atmosphere is closely coupled to the lower atmosphere. Consequently, seasonal and other (e.g., dust storms) variations in the lower atmosphere may affect the state of the upper atmospheric reservoir from which escape occurs and thereby affect escape fluxes. For instance, the transport of water vapor upwards from the lower atmosphere will influence the amount of hydrogen available to escape from the upper atmosphere.

Sub-objective C2: Find physical and chemical records of past climates and factors that affect climate.

Another pathway towards determining the mass, composition, and climate of the ancient atmosphere of Mars is to find physical and chemical records of ancient climates and factors that affect climate. The present geomorphology and geochemistry of features on the surface of Mars record information about the climate from the features' time of formation to the present. For instance, geological features may have been affected by large impacts, episodic volcanism, outflow channel activity, or the presence of large bodies of liquid water - all factors that may also have influenced the local or global climate. Knowledge from physical and chemical records of where and when liquid water existed on the surface would powerfully constrain the history of the ancient climate. In addition, changes in the magnetic field of Mars, which are also marked in the geological record, will have affected the climate by influencing escape processes. Analysis of the relevant physical and chemical records would provide the basis for understanding the spatial extent and timing of the past climates of Mars, as well as whether changes in climate occurred gradually or abruptly. The topography, state of surface volatile reservoirs such as polar caps, and nature and abundance of dust in ancient times are also important for the ancient climate.

This sub-objective will require the application of geological techniques, including determination of sedimentary stratigraphy, which records the history of aqueous processes, and the spatial and temporal distribution of aqueous weathering products, to climate-related questions.

<u>Investigation C2.1:</u> Determine the atmospheric environment required by observed geochemical and geophysical features (High Priority).

<u>Investigation C2.2:</u> Identify the extent of any oceans or large lakes and determine the absolute ages of associated features (Medium Priority).

<u>Investigation C2.3:</u> Determine boundary conditions necessary for climate modeling, including topography, state of polar caps, and state of the magnetic field (Low priority).

Sub-objective C3: Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present.

Knowledge of how the chemical composition and mass of the atmosphere have evolved over the history of Mars is not yet sufficient to constrain the ancient climate of Mars.

High-precision radiometric dating and isotopic measurements of Martian meteorites and returned samples can determine atmospheric properties at the time of the sample's formation. Similar measurements may also be performed in situ by landers. The oldest samples would provide quantitative constraints on the planet's initial atmospheric inventory of gases. The younger samples would provide milestones throughout the atmosphere's evolution that would complement and constrain the findings of other investigations in this Objective.

This Sub-objective will require detailed chemical analyses of Martian samples, either on Earth or in situ.

Investigation C3.1: Measure absolute ages of trapped gases (High Priority).
Trapped gases in rocks provide one of the only ways to directly measure the composition of the ancient Martian atmosphere. Hypotheses of atmospheric loss rate and compositional evolution must be consistent with these trapped gasses. Absolute ages provide the highest level of constraint and most direct measurement of climate evolution. Samples covering key periods of Martian history, from the pre-Noachian to the Amazonian, are likely to provide revolutionary new climate information. This investigation is of high priority for in situ dating and analysis investigations and should be a cornerstone of any sample return mission.

GOAL III: UNDERSTAND THE ORIGIN AND EVOLUTION OF MARS AS A GEOLOGICAL SYSTEM

Objectives	Sub-Objectives
A. Document the geologic record preserved in the crust and interpret the processes that have created it.	**A1:** Identify and characterize past and present geologic environments and processes relevant to the crust.
	A2: Determine the relative and absolute ages of geologic units and events through Martian history.
	A3: Constrain the magnitude, nature, timing and origin of past planet-wide climate change.
B. Determine the structure, composition, and dynamics of the Martian interior and how it has evolved	**B1:** Identify and evaluate manifestations of crust-mantle interactions.
	B2: Quantitatively constrain the age and processes of accretion, differentiation and thermal evolution of Mars.
C. Determine the manifestations of Mars' evolution as recorded by its moons.	**C1**: Constrain the planetesimal density and type within the Mars neighborhood during Mars formation, as implied by the origin of the Mars moons.
	C2: Determine the material and impactor flux within the Mars neighborhood, throughout Mars' history, as recorded on the Mars moons.

Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as providing insight into the history and processes of our own planet. There are compelling scientific motivations for the study of the surface and interior of the planet in its own right. Earthlike (or near-Earthlike) environments— that is, environments similar to that on modern Earth — are rare in the history of the solar system, and Mars represents a planet where such an environment may once have existed. The geology of Mars sheds light on virtually every aspect of the study of conditions potentially conducive to the origin and persistence of life on that planet, and the study of the interior provides important clues about a wide range of topics, such as geothermal energy, the early environment, and sources of volatiles.

Within Objectives A and B, individual objectives, sub-objectives and investigations were examined through the lens of understanding Earthlike environments, and prioritized based on how and at what level each would increase accuracy, be unique or game-changing, or be most likely to yield results in the context of geoscience. As this document is meant to encompass a timeline of a few decades, also taken into account was whether the work needed for major advances in an investigation would constitute a long-term investment (complex, requiring many missions to achieve) or could be achieved rapidly (e.g. substantial advances within the scope of one or two missions). In some cases, a high priority investigation may be prioritized lower than another investigation because its accomplishment is less likely within the timeframe given the state of knowledge/technology. Where investigations were considered equal with respect to other criteria, those supporting other goals were given a higher priority within their sub-objective than those that did not cross-cut other themes.

Objective C focuses on the Mars moons, Phobos and Deimos, and aims to identify science investigations of these components of the Mars system that would yield important insights about the formation and evolution of Mars. Prioritization within this objective reflects the high value of information regarding Mars' formation environment that could be interpreted from knowing the origin of these moons, and the information most needed to answer that question (in light of existing information and understanding).

Objective A: Document the geologic record preserved in the crust and interpret the processes that have created it.

The Martian crust contains the record of processes that shaped it, from initial differentiation and volcanism, to modification by impact, wind, ice, water and other processes. Understanding that record provides clues to reconstructing past and present environments (as reflected, for example, in the alteration mineralogy); the total inventory and role of water, ice and other volatiles; regions likely to have been habitable; processes involved in surface-atmosphere interactions; and the planet's thermal history. Many of the listed investigations are interrelated and could be addressed by common data sets and/or methodologies. In many cases, the reasons for separating some subjects into different investigations have to do with issues of scale (vertical and lateral) or geologic/geophysical process. For the purposes of Goal III, we use the traditional definition of "crust," as the outermost solid shell of Mars, compositionally distinct from deeper layers.

Sub-objective A1: Identify and characterize past and present geologic environments and processes relevant to the crust.

<u>Investigation A1.1:</u> Determine the role of water and other processes in the sediment cycle.

Mars is now recognized as a world with an abundance of sedimentary rocks. More, liquid water was once stable there, and was part of the sedimentary process, making it an extremely rare geologic environment within the solar system. Sediments and sedimentary rocks formed in and near fluvial, lacustrine, or other deposition regimes, record the history of aqueous processes, and are the most likely materials to preserve traces of prebiotic compounds and evidence of life. Aeolian sediments record a combination of globally averaged and locally derived fine-grained sediments and weathering products that feed into the overall sediment budget. Thus, understanding these sedimentary processes would provide a powerful second datapoint, alongside Earth, in understanding the origin and evolution of Earthlike environments. This investigation is meant to be inclusive of processes that are less well-understood, where the mechanism of modification is transient or unclear (e.g. RSLs). This investigation requires knowledge of the ages (A2), sequences, and mineralogies of sedimentary rocks; as well as the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport. The resolution at which such measurements must be taken would be location- and process-specific, but recent advances have demonstrated the value of combining orbital remote sensing images at nested resolutions, and in situ observations at a range of judiciously-chosen scales from meters to microns, to produce detailed reconstructions of past aqueous sedimentary environments.

<u>Investigation A1.2:</u> Identify the geochemical and mineralogic constituents of crustal materials and the processes that have altered them.

Understanding Mars' geologic/environmental history requires quantitative measurement of mineralogy and chemistry. Identification of alteration processes requires characterization of both unaltered and altered rock. Hydrothermal environments in particular provide a potentially unique environmental niche in which life may presently exist, or in which life may have existed in the past. Hydrothermal systems may also play an important role in the chemical and isotopic evolution of the atmosphere. There have been considerable advances in the understanding of surface mineralogy based on remote sensing and limited in situ observations. Orbital remote sensing with high spatial and spectral resolution has demonstrated the ability to correlate mineralogy with specific geologic units. However, calibration of the orbital data with in situ direct determination of mineralogy is critical, both to ensure that the interpretations based on orbital data are correct and to understand those species that either have limited spatial extent or concentration, or which cannot be detected in remote observation.

<u>Investigation A1.3:</u> Characterize the textural and morphologic features of rocks and outcrops.

Observations of rocks and outcrops at resolutions of meters to centimeters can identify a range of important attributes such as sedimentary structures, stratigraphic relationships, and volcanic flow features. Lithological features involving grains and grain relationships 0.5-10 mm in scale (handlens scale) provide key indicators of rock-forming and altering environments, including evidence for past Earthlike environments (e.g., deciphering depositional mechanisms, habitability and characterization of the potential for biosignature preservation). At the microscopic scale (tens of microns or less), grain size and mineralogy can provide clues to the cooling history for igneous deposits or the temperature under which certain minerals formed during water-rock reactions. Minerals in sedimentary environments that are the product of microbial processes may also be identified spectrally. High resolution imaging across a range of scales, ideally in color and stereo, is required.

<u>Investigation A1.4:</u> Identify ice-related processes and characterize how they have modified the Martian surface.

Although many bodies have surface water ice, ice on Mars (and the geologic evidence it leaves) may be studied as an important indicator of changes in the Martian climate. Additionally, ice (water and otherwise) has been, and continues to be, a surface-modifying process on Mars and a reservoir for volatiles. Recognizing the extent of ice at the the poles and other surface and near surface locations is key to evaluating the volatile budget. A range of measurements can be applied to this investigation including active sub-surface sounding, neutron and other spectroscopies, and thermal and visible imaging.

<u>Investigation A1.5:</u> Document the surface manifestations of igneous processes and their evolution through time.

The Martian crust was formed initially through igneous processes. Subsequent volcanic activity dominated the additions to the crust. The surface is overwhelmingly basaltic in composition, and has been dramatically shaped by volcanism. Understanding volcanic and other igneous processes through the record exposed at the surface is crucial for placing other observations in context. This investigation spans the full range of igneous processes and includes the study of the mineralogy and petrology of igneous rocks. Understanding primary igneous lithologies also is a key to interpreting alteration processes that have produced secondary mineralogies. The study of igneous processes requires orbital and surface spectral remote sensing and imaging across a range of resolutions.

Investigation A1.6: Evaluate the effect of large- and small-scale impacts on the nature and evolution of the Martian crust.

Impacts are one of the global processes shaping the crust and surface of Mars. Ubiquitous throughout most of the Solar System, impact structures often have unique characteristics on Mars that reveal clues regarding the nature and composition of the surface and 3-dimensional crust. Additionally, a detailed understanding of effects of impact events (e.g., those producing quasi-circular depressions and basins) on Mars' crust, structure, topography and thermal history, is a prerequisite for any broad understanding of the history of the crust and lithosphere. Understanding impact effects would require geologic mapping using global topographic data combined with high-resolution images and remote sensing data.

Sub-objective A2: Determine the relative and absolute ages of geologic units and events through Martian history.

Investigation A2.1: Quantitatively constrain the absolute ages of the surface and accessible crustal layers.

The evolution of the surface, as well as the evolution of an Earthlike environment, must be placed in an absolute timescale, which is presently lacking for Mars. Currently, the ages of various terrain units on Mars are constrained using crater size-frequency distribution models that are linked to a quasi-absolute timescale from the Moon. But there are major sources of uncertainty with this approach. Developing an accurate chronology requires determining the absolute ages of crystallization or impact metamorphism of individual units with known crater frequencies. This would allow calibration of Martian cratering rates and interpretations of absolute ages of geologic units. Additionally, such calibration could help to constrain the timing of various events throughout the solar system. This investigation could be approached with both in situ and returned sample analysis, although with different precision.

Investigation A2.2: Assess the characteristics of Martian craters and document their distribution.

Impact craters have long been used as an indicator of relative age, to describe how a surface, and the environment of which it retains a record, has changed over time. Craters are a crucial tool in understanding the relative ages of geologic units. However, assessing the Martian cratering record in this light presents difficulties peculiar to Mars. An active erosional and depositional cycle has modifed craters throughout Martian history, and variations in composition and mechanical structure in surface and sub-surface layers affect the morphology of resulting craters, so that direct comparison with crater assessments from small, airless, rocky bodies can be problematic. This investigation will require studies of both individual craters (to assess morphologic characteristics as they relate to crater degradation over time) and crater populations, using topographic data combined with high-resolution images and remote sensing data.

Investigation A2.3: Identify and characterize the distribution, nature, and age relationships of rocks, faults, strata, and other geologic features, i.e., geologic mapping.

Geologic mapping is a comprehensive investigative process that organizes disparate datasets into geologic units with the goal of revealing the underlying geologic processes and placing those processes into a global, contextual framework. A geologic map is a visual representation of the distribution and sequence of rock types and other geologic information. It allows observations to be organized and represented in an intuitive format, unifies observations of heterogeneous surfaces made at different localities into a comprehensive whole, and provides a framework for science questions to be answered. This information can then be used to analyze relationships between these characteristics; this, in turn, can inform models of thermal and structural evolution. Many areas of Mars are mapped at high resolution and are well-understood, while for others this is less true; and the benefits of mapping are highly dependent on the global, regional or local issues being addressed. In general, however, the data required includes correlated high-resolution topographic, compositional and morphologic data.

Sub-objective A3: Constrain the magnitude, nature, timing and origin of past planet-wide climate change.

Investigation A3.1: Identify paleoclimate indicators in the geologic record and estimate their timing and duration.

Evidence for climate change on Mars is based on a variety of observations including ancient valley networks, heavily eroded craters, the presence of various minerals in the stratigraphic record, banded sedimentary deposits, and changes in the polar caps. The study of these and other paleoclimate indicators offers the potential to recognize variations in the Martian climate over time. Relative timing and duration of different climate regimes can in somes cases be estimated from crater size-frequency modeling of appropriate terrain units and superposition relationships. Depending on the nature of a given indicator, a full range of measurements spanning imaging, spectroscopy, and subsurface sounding are needed for this investigation.

Investigation A3.2: Characterize surface-atmosphere interactions as recorded by aeolian, glacial/periglacial, fluvial, chemical and mechanical erosion, cratering and other processes.

The role of atmospheric processes in modifying the surface is most evident among features of the recent past. Dunes and other aeolian bedforms, ice-containing features (including the poles), various erosional features, and even recent impacts provide information on the interaction of the atmosphere with the surface. Studying surficial features resulting from recent atmospheric interactions informs interpretations of features formed in past climates. Orbital and surface-based imaging supplemented by compositional measurements are needed for this investigation.

Investigation A3.3: Determine the present state, 3-dimensional distribution, and cycling of water on Mars, including the cryosphere and possible deep aquifers.

Water is an important geologic agent on Mars and is directly influenced by climatic conditions. Understanding the distribution of water in its various phases and different locations in the current climate provides a basis for interpreting water-related paleoclimate indicators. This invesigation would require global observations using various types of subsurface sounding techniques and remote sensing, coupled with detailed local and regional sounding and measurements.

Objective B: Determine the structure, composition, dynamics, and evolution of Mars' interior and how it has evolved.

Investigating the internal dynamics and structure of Mars would contribute to understanding the bulk chemical composition of the planet, the evolution of its crust, mantle, and core, its thermal evolution, the origin of its magnetic field, and the nature and origin of the geologic units. These are fundamental aspects of Mars that form the basis of comparative planetology.

Sub-objective B1: Identify and evaluate manifestations of crust-mantle interactions.

Investigation B1.1: Determine the types, nature, abundance and interaction of volatiles in the mantle and crust.

The presence and abundance of volatiles in the mantle, especially H_2O, affect its rheology, differentiation, the petrology of magmas, the styles of volcanism, and ultimately the makeup of the atmosphere. The bulk mantle water content remains poorly constrained, which hampers understanding of mantle differentiation and convection. In addition to the study of Martian meteorites, knowledge of mantle volatiles can be gleaned from the characteristics of surface volcanism, the inventory of volatile-bearing primary mineral phases in deep crustal exposures, and ultimately with the return of igneous rock samples.

Investigation B1.2: Seek evidence of plate tectonics and metamorphic activity, and measure modern tectonic activity.

The hemispheric dichotomy and crustal magnetic "stripes" have been hypothesized as manifestations of plate tectonics. But this process has never been unequivocally demonstrated for Mars. If so, it would give us a new view of Mars as an Earthlike planet, as plate tectonics and the resulting cycling of rock-forming elements and volatiles is considered necessary for such an enviroment to be sustained. Possible low-grade metamorphism has been identified via distinct mineral assemblages, but an association with tectonic processes has not. Identifying these processes would require gravity data, deep subsurface sounding (100s of meters to kilometers), detailed geologic and topographic mapping (including impact mapping/studies), and determination of the compositions of major geologic units. Because the present level of seismicity on Mars is essentially unknown, a single, well-coupled seismic station would be of great value as a "pathfinder" for a full network, providing distance to and level of seismicity, and character of seismic signals and noise in this unexplored environment. The accurate localization of marsquakes in space and time provided by a long-term, continuously active seismic network composed of multiple stations would be required to fully understand the distribution and intensity of current tectonic activity.

Sub-objective B2: Quantitatively constrain the age and processes of accretion, differentiation and thermal evolution of Mars.

Investigation B2.1: Characterize the structure and dynamics of the interior.

Understanding the structure and dynamical processes of the mantle and core is fundamental to understanding the origin and evolution of Mars, its surface evolution, and the release of water and atmospheric gases. For example, the thickness of the crust and the size of the core provide strong constraints on the bulk composition of the planet, its thermal history, and the manner in which it differentiated. This investigation requires seismology (e.g., passive and active experiments, and understanding of the seismic state of the planet), heat flow, gravity data, precision tracking for rotational dynamics, and electromagnetic sounding. Because accurate localization of seismic activity is necessary to fully address all objectives, at least four stations operating simultaneously for a full Mars year are required. However, progress in this investigation could be made with a single station. There are a number of techniques available for using single-station seismic, heat flow, and precision tracking data to obtain key information on interior structure and processes. Interpretation of such data depends on models and assumptions, and the results would be biased toward a single region of the planet. However, given the nearly complete lack of data on the Martian interior, results from a single station would represent a significant advance.

Investigation B2.2: Measure the thermal state and heat flow of the Martian interior.

Knowledge of the thermal evolution of the interior places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gases) to the surface. This investigation would require measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships. These data could be obtained through analysis of the seismic velocity profile, heat flow measurements, and study of the mineralogy and geochemistry of xenoliths in volcanic and plutonic rocks.

Investigation B2.3: Determine the origin and history of the magnetic field.

Evidence that Mars had a magnetic field early in its history has important implications for its formation and early evolution, as well as for the retention of an early atmosphere and for the shielding of the surface from incoming radiation. The collection of high-precision, high-resolution global, regional, and local magnetic measurements, calibration of the ages of surfaces, and measurements of the magnetic properties of samples would now be required. Additionally required is high-resolution (spatial and field strength) mapping of the magnetic field and determination of the crustal mineralogy (particularly the magnetic carriers), geothermal gradient, and magnetization of geologic units.

Objective C: Determine the manifestations of Mars' evolution as recorded by its moons.

Sub-objective C1: Constrain the planetesimal density and type within the Mars neighborhood during Mars formation, as implied by the origin of the Mars moons.

The Martian moons, Phobos and Deimos, are generally accepted to be ancient bodies and to have spent most of their history in orbit about Mars. Three main origin hypotheses have been proposed for the Mars moons:

- In the capture model, the moons formed outside the Mars environment (e.g., in the asteroid belt or outer solar system) and then were captured into orbit about Mars, perhaps due to drag from a primordial extended Martian atmosphere or friction within the solar nebula. If the moons were captured, it implies a large population of similarly-sized objects once existed in Mars' vicinity (because the probability of an encounter leading to capture rather than direct collision or scattering is very small).
- In the large impact model, Phobos and Deimos accreted from a disk produced by collision of a 1000-km radius protoplanet with Mars. If the moons formed by impact, the nature of this event would provide new constraints on Mars' late accretion as well as a constraint on the number and energies of the planetesimals in Mars' neighborhood during that period.
- In the co-accretion model, the moons formed in the vicinity of Mars as it grew. Thus, they would be composed of similar material as bulk Mars (having never undergone differentiation). Additionally, the existence of these moons provides constraints on the number and energies of small planetesimals within the Mars neighborhood during early Mars accretion.

Regardless of which hypothesis is correct, knowing the origin of these moons will provide useful information about the early formation of Mars (either during its accretion or soon after) that cannot be determined through other means. Thus, determining the origin of these moons is of highest priority within this objective. Investigations outlined below are defined and prioritized so as to enable this aim.

Note that the moons may not share an origin, which makes it important to investigate both moons. If they do share an origin, then the data returned will be strengthened by having two "data points". If they do not share an origin, then perhaps more information could be gleaned about Mars' formation history.

Investigation C1.1: Interpret the geologic history of the moons, by identification of geologic units and the relationship(s) between them (time-order, weathering, etc.).

Although many observations exist of these moons – especially Phobos (including some higher resolution spectra and images by MRO and MEx), there is much disagreement about what these observations imply about the moon's origin. Additionally, existing observations of spectral heterogeneity imply that there are two endmember units on each moon (generally referred to as "red" and "blue"). The spatial and/or genetic relationship between these units and which, if either (or both), is representative of "original" material, and thus most useful for using as a discriminator between origin hypotheses, remains unclear. Finally, there are questions about the amount and distribution of "contamination" materials, consisting of ejecta from Mars, ejecta/dust shared between the moons, or exogenic materials. Thus, it has become clear that an understanding of the geologic history of these moons is a necessary precursor to interpretation of composition and other observations.

Investigation C1.2: Determine the composition of rock and regolith on the moons, including elemental and mineralogical compositions.

The composition of these moons promises to be the clearest discriminator between origin theories. In particular, certain elemental abundances can differentiate between abundances measured on Mars and those measured within meteoritic samples. Some of these elemental abundances would also be unaffected by space weathering and impact processes which may have altered the surfaces of these moons since their origin. Resolution of these observations needs to be sufficient for association with distinct geologic units.

Investigation C1.3: Characterize the interior structure of the moons to determine the reason for their bulk density and the source of density variations within each moon (e.g., micro- vs. macroporosity).

Models of the orbits of these moons shows that collision between the two moons was likely, on timescales shorter than the ages of the moons. Thus, both the interior structure and the orbits of these moons may not be strict representatives of their original state, and thus are more difficult to interpret as indicators of the moons' origin. However, there are measurements of the moons' interiors that could serve as records of each moon's original state. In particular, determining the reason for the bulk density and density variations within each moon may give some indication if the moon had originally been monolithic (implying a capture origin) and/or contain(ed) volatile reservoirs (again, implying a capture origin).

Sub-objective C2: Determine the material and impactor flux within the Mars neighborhood, throughout Mars' history, as recorded on the Mars moons.

Investigation C2.1: Measure the character and rate of material exchange between Mars and the two moons.

As noted above, material may have been exchanged (and continue to be exchanged) between the Mars moons and Mars. Constraining this exchange is a needed input to the origin sub-objective (see Investigation C1.1). Additionally, an estimation of the dust exchange rate between the moons would feed into studies of the theorized dust torus (which is of interest to Goal IV: Investigation C2.1). Finally, the moons perhaps can serve as a witness plate for Mars ejecta, for understanding Martian meteorites found on the Earth.

Inverstigation C2.2: Understand the flux of impactors in the Martian system, as observed outside the Martian atmosphere.

As these moons have been in orbit around Mars, and have been tidally locked with Mars for much of their history, they present records of the impactor flux experienced by Mars.

GOAL IV: PREPARE FOR HUMAN EXPLORATION

Objectives	Sub-Objectives
A. Obtain knowledge of Mars sufficient to design and implement a human mission to Mars orbit with acceptable cost, risk and performance.	**A1.** Determine the aspects of the atmospheric state that affect aerocapture and aerobreaking for human-scale missions at Mars.
	A2. Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Martian system.
B.Obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with acceptable cost, risk and performance.	**B1.** Determine the aspects of the atmospheric state that affect Entry Design and Landing (EDL) design, or atmospheric electricity that may pose a risk to ascent vehicles, ground systems and human explorers.
	B2. Determine if the Martian environments to be contacted by humans are free of biohazards that might have adverse effects on the crew that might be directly exposed while on Mars, and on other terrestrial species if uncontained Martian material would be returned to Earth.
	B3. Determine the Martian environmental niches that meet the definition of "Special Region."
	B4. Characterize the particulates that could be transported to hardware and infrastructure through the air (including natural aeolian dust and other materials that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and in situ lifetime.
	B5. Understand the resilience of atmospheric ISRU processing systems to variations in martian near-surface environmental conditions.
	B6. Assess landing site-related hazards, including those related both to safe landing and safe operations (includng trafficability) within the possible area to be accessed by elements of a human mission.
	B7. Assess risks to crew health and performance by (1) characterizing in detail the ionizing radiation environment at the Martian surface and (2) determining the possible toxic effects of Martian dust on humans.
C. Obtain knowledge of Mars sufficient to design and implement a human mission to the surface of either Phobos or Deimos (P/D) with acceptable cost, risk and performance.	**C1.** Understand the geological, compositional and geophysical properties of P/D sufficient to establish specific scientific objectives, operations planning, and any potentially available resources.
	C2. Understand the conditions at the surface and the low orbital environment for P/D sufficiently to be able to design an operations plan (including close proximity and surface interactions).
D. Obtain knowledge of Mars sufficient to design and implement sustained human presence at the martian surface with acceptable cost, risk and performance.	**D1.** Characterize potentially extractable water resources to support In Situ Resource Utilization (ISRU) for long-term human needs.

Editorial Note: In revising the following section, a number of subject matter experts (both Mars flight investigators and HEOMD technical personnel) were contacted regarding various technical details. This information was synthesized by the editors of this document into the structure that follows. However, by means of this review copy, we are seeking two specific kinds of feedback:

1. Additional technical information that has a bearing on the statements and priorities described,

2. Comments on the way we have integrated the information—does this adequately represent the big picture, and in a way that is acceptable to the stakeholders?

Goal IV encompasses the use of robotic flight missions to Mars to prepare for potential human missions (or sets of missions) to the Martian system. In broadest context, Mars is a partially unknown place, and our partial or missing knowledge creates risk to the design and implementation of a human mission. Many important risks can be "bought down" by means of acquiring precursor information, in order to allow for better-informed architectural, design, and operational decisions. In the same way that the Lunar Orbiters, Ranger and Surveyor landers paved the way for the Apollo Moon landings, the robotic missions of the Mars Exploration Program can help chart the course for potential future human exploration of Mars. This is not to say that all risks need to be reduced by means of precursor knowledge—for some risks, acquiring the knowledge is more expensive than engineering against the problem. For others, it may be acceptable to simply accept this risk. This set of issues was most recently considered in detail by P-SAG (2012), who proposed the set of investigations that flowed into the 2012 version of the MEPAG Goals Document (MEPAG, 2012).

It is also worth note that preparing for the human exploration of Mars would involve precursor activities in several venues other than Mars, including on Earth (e.g., in laboratories, in computers, and in field analogs), in low Earth orbit (including the International Space Station), and probably on nearby celestial objects such as the Moon and asteroids. Although all are important, the scope of this document is limited to precursor activity related to the Mars flight program. If connectivity between various precursor activities needs to be maintained, it would be done separate from this document.

Changes to Goal IV since 2012

The 2012 version of Goal IV benefitted from a consideration of the P-SAG (2012) committee report. Since then, there has not been a successor analysis of that character. However, significant progress has been made on several of the investigations called for by P-SAG (2012), most importantly by the Mars Science Laboratory (MSL) mission, which successfully landed on Mars in August, 2012. MSL carried two sensors that were directly in support of Goal IV; the Radiation Assessment Detector (RAD[2]), and Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI[3]). In addition, several of the scientific instruments on MSL have made measurements of the Martian environment and/or materials of relevance to the investigations described in Goal IV. As of this writing, MSL has completed its prime mission, and has been approved for an extended mission—thus, data of relevance (including from RAD) continues to flow in.

[2] http://mars.jpl.nasa.gov/msl/mission/instruments/radiationdetectors/rad/
[3] http://mars.jpl.nasa.gov/msl/mission/instruments/atmossensors/medli/

In addition, the Mars Reconnaissance Orbiter (MRO), which began its observing campaign at Mars in 2006, has continued collecting data from Mars since the 2012 MEPAG Version. Of particular significance to Goal IV is the major atmospheric instrument MCS, the HiRISE imager, and the CRISM spectrometer. All of these instruments had been in service for several years prior to P-SAG's analysis of Goal IV needs as of 2012, but additional data since 2012 have yielded significant discoveries and observations.

In sum, as of 2015, the results from these missions have made partial to full progress within several of the investigations described in the 2012 version of the Goals Document. This has resulted in the retiring of three previously described investigations (those that we propose retiring are highlighted in blue), a narrowing of the statement of required additional investigation for several others, and for a few, a reduction in the priority of additional precursor information.

The structure and priority of objectives within Goal IV

In order to properly inform the Goal IV objectives and set relative priorities, reference mission concepts are required. Over the years many design reference studies for humans to Mars have been conducted. These studies demonstrate that the key objectives and investigations should be prioritized primarily by the expected sequence of mission types rather than the changeable variation of potential transportation architectures.

Key Mars Reference Architecture Studies: The most recently NASA published human exploration of Mars mission concept is the Design Reference Architecture (DRA) 5.0[4] (Drake, 2009). Based on this document, major revisions of Goal IV were made in 2010 (MEPAG, 2010), focusing on the re-prioritization of investigations with inputs from Mars robotic missions and DRA 5.0 findings.

Currently, NASA is considering how a human Mars exploration program, such as the one articulated in DRA 5.0, fits within the broader goals of a larger human exploration strategy. To that end, a white paper on "Pioneering Space" was issued by NASA in May of 2014[5]. The long-term, flexible and sustainable deep space exploration architecture that fullfills the principles in "Pioneering Space" is being termed the Evolvable Mars Campaign (EMC). Wtihin the EMC, the primary strategic change from DRA 5.0 is the preference for a single landing site which will be used for a series of human surface missions. This strategy puts greater emphasis on connecting sustained human presence to the first human landings.

Within the Goal IV version presented here, investigations have been re-prioritized to reflect this change in emphasis. However, all of the gap-filling activities (GFAs) remain the same and the prioritization of GFAs in the 2010 Goal IV revision is still valid.

Sequence of Mission Types: Each human mission concept for Mars includes the need for precursor data, and the exact requirements may differ between mission concepts. But while there are many architectural choices available to conduct a given mission type, the precursor investigations required to execute a human Mars mission is dependent primarily on the whether or not the mission is to Mars orbit-only, Phobos/Deimos-only, or all the way to Mars surface, and the subsequent timing to implement sustained presence on the surface.

[4] http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf
[5] http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf

For the purposes of Goal IV and in the context of a logical sequence within a human Mars exploration program, the human mission types were assumed to follow a defined order, with missions to Mars orbit or Phobos/Deimos optionally happening before missions to the Martian surface. Sustained human presence was assumed to happen long after the first missions to the Martian surface. P-SAG (2012) initially drew the above distinctions, and they used the terminology “Goal IV-” (human missions to Martian orbit), “Goal IV” (human missions to the Martian surface), “Goal IV- P/D” (human missions to Phobos/Deimos), and “Goal IV+” (sustained presence). By means of this document, we are updating this nomenclature to a more conventional objective structure:

A. A human mission to Mars orbit
B. A human mission to the Martian surface
C. A human mission to the surface of either Phobos or Deimos
D. Sustained human presence at the Martian surface

An important point is that the precursor data needed to achieve Objective A enables Objective B, C, and D, since it is necessary to interact with the Martian upper atmospheric and orbital environment to achieve any of the latter. Achieving A and B is necessary to achieve D. However, C is independent of B and D. These relationships establish the overall structure of the sections that follow.

Objective A	Objective B	Objective C	Objective D
			
Human missions to Mars orbit as a precursor to Mars surface missions (optional).	Human missions to the Martian surface.	Human missions to Phobos and/or Deimos as a precursor to Mars surface missions (optional).	Sustained human presence on Mars. Follows Mars surface missions.

Figure IV-1: *Types of human missions to the Martian system. The missions appear in time sequence from left to right. Note that the Objective A and Objective C missions are optional.*

This defines a time series for when knowledge is needed. The precursor knowledge related to Objective A is the foundation for all other pathways, and is thus deemed of paramount strategic importance. The precursor information needed for Objective B and C cannot currently be distinguished in a time sense, because this is at least partially dependent on future political priorities, and engineering realities that cannot be forecasted. However, since Objective D would need to happen after Objective B, it has lower time-urgency.

Finally, it is worth noting that the intrinsic value of the precursor robotic program is to reduce cost and risk to "acceptable" levels (and this language appears in all four objectives below). Ultimately these are parameters that have to be determined by the space agencies who fund the exploration, and their respective citizens. We don't know in 2015 what the threshold values are, and in fact, they change with time. This creates some ambiguity with regards to what is “required” and what is “desired” in Goal IV. In the sections that follow, the priorities reflect our best current understanding of consensus positions regarding the importance of the categories of precursor knowledge, relative to our strategic knowledge gaps.

Prioritization: In setting the priorities in this document, these timing matters were considered in addition to the P-SAG priorities. GFAs needed earlier occur at higher priority than those needed later. (Appendix 4, Table App. 4-1 shows the mapping of the P-SAG priorities and timing into the priorities in this document.) Note that in this document assignment of a specific sub-objective to a priority level is based on the highest priority GFA/investigation within that sub-objective.

P-SAG (2012) based its analysis on of priorities on the ability of each GFA to address the issues related to increasing safety, decreasing cost, and increasing the performance of human missions to Mars. The criteria are listed in Table IV-1.

Table IV-1*: Prioritization criteria used in this document.*

Priority	Definition
High	Recognized as enabling a critical need or mitigating high risk items
Medium	Enables important but not critical need or mitigates moderate risk items
Low	Enhances mission or mitigates lower risk items

Objective A: Obtain knowledge of Mars sufficient to design and implement a human mission <u>to Mars orbit</u> with acceptable cost, risk and performance.

Sub-objective A1: Determine the aspects of the atmospheric state that affect aerocapture and aerobreaking for human-scale missions at Mars. (High Priority)

The atmospheric precursor data requested in this sub-objective is a high priority as it would provide (1) mission-enabling observations and (2) a reduction in the risk of loss of crew and loss of mission by reducing the risk associated with aerocapture and aerobraking. The level of acceptable risk is much lower for manned missions than robotic landers and significant additional atmospheric measurements would be required to support the engineering design and modeling fidelity necessary to reduce the risk. Thus, observations associated with Sub-objective A1 would also be mission-enabling.

Investigations listed in this Sub-objective include characterizing the variability on diurnal, seasonal and inter-annual scales from ground to >80 km in ambient and a range of dust storm conditions. The observations are to directly support engineering design and to assist in numerical model validation, especially the confidence level of the tail of dispersions (>99%).

The global nature of these investigations (spatially and temporally) provides context for weather prediction during critical events. Atmospheric temperatures (Investigation A1.1) would provide the density information necessary to determine entry trajectories, atmospheric heating, and deceleration rates. Aerosol information (Investigation A1.2) is primarily necessary to understand

and model the performance of guidance systems (especially optical systems). A better understanding of winds (Investigation A1.3) would help enable pinpoint landing of surface systems.

Priority	P-SAG GFAs	MEPAG Investigations
High	A1-1. Global temperature field	A1.1: Make long-term (> 5 Martian year) observations of the global atmospheric temperature field (both the climatology and the weather variability) at all local times from the surface to an altitude >80 km. The global coverage would need observations with a vertical resolution ≤ 5 km as well as observations with a horizontal resolution of ≤ 10 km (the horizontal and vertical resolutions do not need to be met by the same observation).
High	A1-2. Global aerosol profiles and properties	A1.2: Make global measurements of the vertical profile of aerosols (dust and water ice) at all local times between the surface and >60 km with a vertical resolution ≤ 5 km. These observations should include the optical properties, particle sizes and number densities.
High	A1-3. Global winds and wind profiles	A1.3: Make long-term (> 5 Martian year) observations of global winds and wind direction with a precision ≤ 3 m/s at all local times from 15 km to an altitude > 60 km. The global coverage would need observations with a vertical resolution of ≤ 5 km and a horizontal resolution of ≤ 300 km.

Sub-objective A2: Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo and crew to the Martian system. (Medium Priority)

There may be a dust ring between Phobos and Deimos located in and around the equatorial plane of Mars (also mentioned in Goal III, Sub-Objective C2.1). Knowledge of the presence of these particulates and their size frequency distribution would help mission architecture planning and engineering designs for cargo and human missions to Mars orbit.

Priority	P-SAG GFAs	MEPAG Investigations
Medium	A3-1. Orbital particulate environment	A2.1: Determine spatial variation in size-frequency distribution of Phobos/ Deimos ejecta particles in Mars orbit.

Objective B: Obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with acceptable cost, risk and performance.

To achieve Objective B, the investigations in Objective A should be completed, along with the following investigations. For the purposes of priority, sub-objectives were grouped into two priority levels and no attempt was made to order investigations within each priority level. Sub-objectives B1-B5 are judged to be of indistinguishable high priority, and B6-B7 are of indistinguishable medium priority.

Sub-objective B1: Determine the aspects of the atmospheric state that affect Entry Design and Landing (EDL) design, or atmospheric electricity that may pose a risk to ascent vehicles, ground systems and human explorers. (High Priority)

The investigations listed in this Sub-objective are designed to fulfill the needs of the consulted EDL engineers; in particular, those working on design studies for human class (~40t) landing systems for Mars. The observations are designed to both directly support engineering studies and validate atmospheric numerical models. The latter are essential to characterize the potential dispersion of parameters. Recent observations fulfill some of the investigation requirements, but are insufficient to provide the necessary fidelity for the engineering modeling. The current orbital record is not yet long enough and fails to provide good coverage at a range of local times. The surface observations are both too short and only exist at four locations.

As with Sub-objective A1, these investigations are global in nature and for similar reasons. As above, it provides context for weather prediction during critical events. Additionally global coverage avoids having to limit site selection due to lack of observations. Local time coverage may allow access to sites otherwise deemed dangerous when conditions are safe. The dust activity climatology (Investigation B1.1) is primarily designed to understand the statistical frequency of events and their expected durations (to determine the necessary margins for waiting them out in orbit or on the surface). Surface pressure (Investigation B1.2) directly controls the total atmospheric mass and thus the altitude of critical events during EDL. A better understanding of winds (Investigation B1.3) would help enable pinpoint landing of surface systems. Even though several robotic missions to Mars surface have successfully entered the atmosphere and landed, the measurements made during a given EDL (Investigation B1.4) only provide a thin slice through the atmosphere at a single instant in time.

Atmospheric electricity (Investigations B1.5-7) has posed a hazard to aircraft and space launch systems on Earth, and might pose similar danger on Mars. One notable incident was the lightning strike that hit the Apollo 12 mission during the ascent phase, causing the flight computer in the spacecraft to reset. Far from a random event, the strike was likely triggered by the presence of the vehicle itself, combined with its electrically conducted exhaust plume that provided a low resistance path to the ground. Future explorers on Mars might face similar risks during Mars Take-off And Orbit insertion (MTAO) after the completion of their mission due to charge suspended in the atmosphere by local, regional or global dust activity. The amount of charge contained in these events, their spatial and temporal variations, and discharge mechanisms remain largely unknown. Surface measurements of electrodynamic phenomena within the atmosphere (i.e., below the ionosphere) could reveal whether or not charge buildup is sufficient for large scale discharges, such as those that affected Apollo 12.

Electrified dust and discharge processes may also represent a hazard during surface operations, effecting everything from static-discharge sensitive equipment to communications. Unknown frictional charging interactions (“triboelectricity”) between EVA suits, rovers, and habitats might also come into play. Understanding the ground and atmospheric conductivity, combined with the electrical properties of dust, would help to constrain the magnitude of these risks.

Implementation Considerations: We have not reached agreement on the minimum number of atmospheric measurements described above, but it would be prudent to instrument all Mars atmospheric flight missions to extract required vehicle design and environment information. Our current understanding of the atmosphere comes primarily from orbital measurements, a small number of surface meteorology stations and a few entry profiles. Each landed mission to Mars has the potential to gather data that would significantly improve our models of the Martian atmosphere and its variability. It is thus desired that each opportunity be used to its fullest potential to gather atmospheric data. Reconstructing atmospheric dynamics from tracking data is useful but insufficient. Properly instrumenting entry vehicles would be required.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
High	B1-1. Dust Climatology	B1.1: Globally monitor the dust and aerosol activity, especially large dust events, to create a long-term dust activity climatology (> 10 Martian years).
High	B1-2. Global surface pressure; local weather	B1.2: Monitor surface pressure in diverse locales over multiple Martian years to characterize the seasonal cycle, the diurnal cycle (including tidal phenomena) and to quantify the weather perturbations (especially due to dust storms). The selected locations are designed to validate global model extrapolations of surface pressure. The measurements would need to be continuous with a full diurnal sampling rate > 0.01 Hz and a precision of 10-2 Pa. Surface meteorological packages (including temperature, surface winds and relative humidity) and upward looking remote sounding instruments (high vertical resolution temperature and aerosol profiles below ~10 km) would be necessary to validate model boundary schemes.
High	B1-3. Surface winds	B1.3: Simultaneous with the global wind observations, profile the near-surface winds (< 15 km) with a precision ≤ 2 m/s in representative regions (plains, up/down wind of topography, canyons). The boundary layer winds would need a vertical resolution of ≤ 1 km and a horizontal resolution of ≤ 100 m. The surface winds would be needed on an hourly basis throughout the diurnal cycle. During the daytime (when there is a strongly convective mixed layer), high frequency wind sampling would be necessary.
Medium	B1-4. EDL profiles	B1.4: Measure occasional temperature or density profiles with vertical resolutions < 1 km between the surface and 20 km.
Low	B1-5. Atmospheric Electricity conditions	B1.5: Combine the characterization of atmospheric electricity with surface meteorological and dust measurements to correlate electric forces and their causative meteorological source for more than 1 Martian year, both in dust devils and large dust storms. B1.6: Determine if higher frequency (AC) electric fields are present between the surface and the ionosphere, over a dynamic range of 10 uV/m – 10 V/m, over the frequency band 10 Hz-200 MHz. Power levels in this band should be measured at a minimum rate of 20 Hz and also include time domain sampling capability. B1.7: Determine the electrical conductivity of the Martian atmosphere, covering a range of at least 10-15 to 10-10 S/m, at a resolution ΔS= 10% of the local ambient value.

Sub-objective B2: Determine if the Martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards that might have adverse effects on the crew that might be directly exposed while on Mars, and on other terrestrial species if uncontained Martian material would be returned to Earth. (High priority)

Note that determining that a landing site and associated operational scenario would be sufficiently safe is not the same as proving that life does not exist anywhere on Mars.

The Investigations described in this Sub-objective would aid in reducing risks to acceptable, as-yet undefined, standards as they pertain to: (1) the human flight crew, (2) the general public, and (3) terrestrial species in general. The risks in question relate to the potential exposure of humans and othere terrestrial species to uncontained Martian material, such as regolith and dust, that would certainly be on the outside of the ascent vehicle, within the cabin, or even within the astronauts' bodies when the crew leaves Mars. As shown by our experience with Apollo, when the crews open the seals to their landed systems to carry out EVA explorations, it is impossible to avoid getting dust on the outsides of the spacesuits as well as into the living quarters. A step called "breaking the chain of contact" is necessary to manage this risk. Although this is believed to be technically possible for robotic missions, it is not for a crewed mission. Because on a mission to the Martian surface it would not be possible to prevent human contact with the dust, it is necessary to determine in advance whether or not that dust is biologically hazardous. The action of returning the astronauts to Earth at the end of the mission, along with any associated uncontained Martian material, could pose a low but as-yet undefined risk to the Earth's ecosystem. For this reason, the impact of the data from this sub-objective on mission design has been rated high (mission enabling) and the impact of the data on risk reduction has also been rated high (public safety), for a combined priority rating of high.

Priority	P-SAG GFAs	MEPAG Investigations
High	B2-1. Biohazards	B2.1: Determine if extant life is widely present in the Martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard. For both assessments, a preliminary description of the required measurements is described in the MSR Draft Test Protocol (Rummel et al., 2002). This test protocol would need to be regularly updated in the future in response to instrumentation advances and a better understanding of Mars and of life itself.

Sub-objective B3: Determine the Martian environmental niches that meet the definition (as defined by COSPAR) of "Special Region." (High Priority)

It is necessary to consider both naturally occurring special regions and those that might be induced by the (human-related) missions envisioned. Evaluate the vulnerability of any Special Regions identified to terrestrial biological contamination, and the rates and scales of the Martian processes that would allow for the potential transport of viable terrestrial organisms to these special regions.

The Investigations described in this Sub-objective relate to characterizing "Special Regions" on the Martian surface, either extant or possibly induced by a human mission. One of the major mission objectives of the proposed human mission would be to determine if and how life arose naturally on Mars. Therefore, data that contributes to the understanding of the location of extant

Special Regions where Martian life could exist is considered of the highest priority (mission enabling). This mission objective could be compromised, however, by inducing a Special Region through the engineering aspects and biological inputs innate to a human mission. Evaluating the extent of this potential compromise would require data from the Investigations described below.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
High	B5-1. Identify and map special regions	B3.1: Map the distribution of both naturally occurring special regions, and regions with the potential for s/c induced special regions, as defined by COSPAR5. This analysis needs to be done periodically to incorporate all spacecraft-sourced discoveries since the last analysis. One key investigation strategy is change detection surveys.

Sub-objective B4: Characterize the particulates that could be transported to hardware and infrastructure through the air (including natural aeolian dust and other materials that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and in situ lifetime. (High Priority)

Mars is a dry, dusty place. We need to understand the potential impacts of dust on the surface system. There are at least three potential deleterious effects that need to be understood: (1) effects of dust on seals, especially seals that need to be opened and then reestablished, (2) effect of dust on the electrical properties of the surfaces on which it would accumulate (for example, the effect of dust on circuit boards), and (3) the corrosive chemical effects of Martian dust on different kinds of materials. Note that for the purpose of this Sub-objective, we distinguish between the direct effects of Martian dust on human beings (Sub-objective B7, below) and the effect of dust on the engineering system that would keep the humans on Mars alive and productive.

Past experience with lunar surface astronaut operations as part of the Apollo program showed that it would be difficult, if not impossible, to prevent dust from getting into different parts of a landed system on Mars. On the Moon, there were three primary anthropogenic dust-raising mechanisms (ranked according to increased importance): astronaut walking, rover wheels spinning up dust, and landing and takeoff of spacecraft. These three mechanisms would also be relevant for a Martian surface mission, but on Mars there would additionally be a fourth—winds that are capable of raising and transporting dust.

Significant data about dust properties, dust accumulation rates, and effects on mechanical surface systems on Mars have been obtained from MER (Opportunity and Spirit), Phoenix, and MSL (Curiosity), thus the impact of additional investigations of these properties are now ranked lower than in previous versions of this document. However, measurements of these properties *at other sites* would help to determine the range of conditions expected and might still have an impact on mission design. Furthermore, there remains a dearth of data regarding the electric and thermal conductivity, triboelectric and photoemission properties and associated chemistry of the fines.

This Sub-objective requires collecting enough data about Martian dust to be able to create a large quantity of a Martian dust simulant that could be used in engineering laboratories on Earth. These data would be best obtained by analysis of a returned sample.

Priority	P-SAG GFAs	MEPAG Investigations
Low	B4-1. Electricity	B4.1: Determine the electrical conductivity of the ground, measuring at least 10-13 S/m or more, at a resolution DS of 10% of the local ambient value. B4.2: Measure the magnitude and dynamics of any quasi-DC electric fields that may be present in the atmosphere as a result of dust transport or other processes, with a dynamic range of 5 V/m-80 kV/m, with a resolution DV=1V, over a bandwidth of DC-10 Hz (measurement rate = 20 Hz). B4.3: Determine the charge on individual dust grains equal to a value of 10-17 C or greater, for grains with a radius between 1-100 mm.
High	B4-2. Dust physical, chemical and electrical properties	B4.4: Analyze regolith and surface aeolian fines (dust), with a priority placed on the characterization of the electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations. Partial information exists on shape and size distribution, density, shear strength, ice content and composition, and mineralogy, especially from Gale Crater, and these data should be extended to at least one other site with different geologic terrain.
Medium	B4-3. Regolith physical properties and structure	B4.5: Regolith particle shape and size distribution, as well as Flow Rate Index test or other standard flow index measurement on the regolith materials. B4.6: Determine the chemistry and mineralogy of the regolith, including ice contents. This investigation has been completed by MSL at Gale Crater, and these data should be extended to at least one other site.

Sub-objective B5: Understand the resilience of atmospheric ISRU processing systems to variations in Martian near-surface environmental conditions. (High Priority)

We propose deleting the text highlighted in blue, if the Investigations are considered retired.

Future crewed Mars missions will be enabled by using in situ resources to produce oxygen for propellant and other consumables. Key trades include quantifying the mass, power, and risk associated with the equipment necessary to acquire and process atmosphere-sourced commodities compared to the mass, power, and risk of simply delivering them from Earth. In Situ Resource Utilization (ISRU) has been a staple of human exploration architecture for Mars since the NASA Design Reference Missions of the 1990s, employed in the form of the simple-to-implement Sabatier reaction, $CO_2 + 4H_2 = CH_4 + 2H_2O$. Sabatier does, however, require carrying H_2 as a consumable.

However, we do not understand in sufficient detail the effects of the Martian environment near the surface on a potential ISRU atmospheric processing system, and what it would take to operate one within acceptable risk for human missions. Two important things to learn are (1) resilience with respect to dust and other environmental challenges, and (2) knowledge of performance parameters that are critical to the design of a full-scale system. In response to this, NASA has selected the MOXIE investigation as part of the payload of the M-2020 rover. MOXIE is the next logical step after laboratory investigations in simulated environments, and is planned to obtain such knowledge through operation of an ISRU plant under actual Mars mission conditions of launch and landing, dust, wind, radiation, electrostatic charging and discharge, thermal cycles, low gravity (which affects convection), and enforced autonomy. Because the Martian atmosphere is well-mixed, only a single advance measurement is expected to be needed.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
High	B6-1. Dust physical, chemical and electrical properties	*[Same as GFA B4-2/Investigation B4.2 above]* B5.1: Analyze regolith and surface aeolian fines (dust), with a priority placed on the characterization of the electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations. Partial information exists on shape and size distribution, density, shear strength, ice content and composition, and mineralogy, especially from Gale Crater, and these data should be extended to at least one other site with different geologic terrain.
Low	B6-2. Dust column abundances	B5.2: Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the Martian atmosphere.
Low	B6-3. Trace gas abundances	B5.3: Measure the trace gas composition of the Martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU.
High	NEW	B5.4: Test ISRU atmospheric processing system to measure resilience, with respect to dust and other environmental challenges, of performance parameters that are critical to the design of a full-scale system.

Sub-objective B6: Assess landing site-related hazards, including those related both to safe landing and safe operations (includng trafficability) within the possible area to be accessed by elements of a human mission. (Medium Priority)

Landing and working on Mars means interacting with the Martian surface, which is mostly regolith. Therefore it is important to understand certain properties of the Martian regolith in order to design and operate systems on Mars. Specific areas where information is required/desired include:

Rocket Exhaust Cratering: Landing on Mars with human-scale systems will likely include rocket propulsion to slow the vehicle down for landing. Blast ejecta from descent engines could exceed the bearing capacity of soils, as demonstrated on the Phoenix and MSL missions. This can lead to excavation of holes under the landers as well as the ejection of materials that potentially damage other systems at the landing site.

Bearing Strength: Both landing and the construction of habitats and other facilities would require a surface with sufficient bearing strength to handle the load placed on the surface. In addition, excavation to establish foundations or to provide protection from the surface environment by, for example, burying habitats beneath the regolith to provide protection from radiation, would require understanding subsurface structure of the regolith in order to design and operate systems capable of excavating and using the regolith materials.

Landing site hazards: We know from experience with site selection for past robotic landers/rovers that sites with some of the most interesting scientific attributes also tend to have more difficult and risky terrain. We know from experience with prior Mars landers that the following four factors are particularly relevant to safe landing: the size and concentration of surface rocks, terrain slopes, and the concentration of dust. The specific safety thresholds for these parameters would depend on the specific design of the mission (for example, ground clearance provided by landing legs), but we know from prior experience that these factors have to be considered carefully for all landed missions at Mars.

Trafficability: In order for landed human missions to achieve their objectives, movement across the Martian surface would be required. This might manifest itself in establishing and maintaining necessary surface infrastructure, or in accessing specific scientific targets. Thus, trafficability hazards need to be considered. In the case of MER, both Spirit and Opportunity became embedded in soft soil while driving. Opportunity was able to extricate itself and continue driving, but Spirit was not. Other trafficability hazards include rock fields and steep slopes.

Current Context:

1. We have a relatively good understanding of the size and shape distributions (roughly known), density, cohesion, angle of internal friction, bearing strength, shear strength, composition, mineralogy (particularly major minerals), and variations of these properties for wind-blown deposits (e.g., ripples encountered at Meridiani and Gale) and soils (planetary soils, defined as mix of locally produced and transported materials, without organic implications) such as found by the Viking Landers, Pathfinder, Phoenix, Spirit, and Curiosity (hummocky plains). We also know a bit about what makes the soils cohesive, dominated by sulfate-rich salts.
2. We know about the ice content of the regolith from Phoenix data for the small areas examined. It ranges from pore ice to slabby ice. The slabby ice was not analyzed using either MECA or TEGA, so for that we have just remote sensing data. We can model the presence of pore ice but not slabby ice, perhaps unless the slabby ice contains salts.
3. We have knowledge about rock coatings, as well as their erosional products in the form of loose dust. They are not Mn-rich as commonly found on Earth, but rather Fe-oxide rich.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
Medium	B7-1. Regolith physical properties and structure	B6.1: Determine regolith physical properties and structure, including surface bearing strength; presence of significant heterogeneities or subsurface features of layering; and an index of shear strength. B6.2: Measure gas permeability of the regolith in the range 1 to 300 Darcy with a factor of three accuracy.
Medium	B7-2. Landing	B6.3: Image selected potential landing sites to sufficient

	site selection	resolution to detect and characterize hazards to both landing and trafficability at the scale of the relevant landed systems.
Low	B7-3. Trafficability	B6.4: Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements. B6.5: Determine vertical variation of in situ regolith density within the upper 30 cm for rocky areas, on dust dunes, and in dust pockets to within 0.1 g cm3.

Sub-objective B7: Assess risks to crew health and performance by (1) characterizing in detail the ionizing radiation environment at the Martian surface and (2) determining the possible toxic effects of Martian dust on humans. (Medium Priority)

Successful human missions to the Mars surface require a functional crew free from debilitating health risks imposed by the Martian environment. The primary gaps in knowledge about potential harmful effects include the radiation environment and dust toxicity of surface regolith.

Risks to astronauts from radiation in space have been characterized for decades. Outside the protection of Earth's magnetic field and atmosphere, the ever-present flux of galactic cosmic rays (GCRs) poses a long-term cancer risk. The particle energies in GCRs are so powerful that using shielding mechanisms as a mitigation would be possible but impractical in most situations. Superimposed on the continual GCR background are solar energetic particles (SEPs), generated episodically by a component of solar activity known as coronal mass ejections (CMEs). SEPs are composed primarily of protons, generally lower in energy than GCRs, and possess much higher number fluxes. An individual SEP event could be fatal to a crewmember if a crewmember is caught unprotected. Given the energy distribution and fluxes of typical SEP events, the use of shielding to mitigate their impact is feasible but shielded areas might be limited in size due to mass constraints. Hence, avoiding SEP exposures would rely primarily on gaining an understanding of space weather, with predictive and monitoring capabilities for CMEs and the SEPs that commonly accompany them. By having such knowledge, precautionary measures and appropriate actions could be taken.

The central issue with radiation exposure on Mars involves validating tools designed to simulate and predict the biological relevancy of being exposed to radiation on Martian surface by taking into account all of the major variables. The Martian atmosphere is geometrically thinner and of lower density than Earth's, and lacks adequate global, intrinsic magnetic field, thus posing a higher risk to radiation exposure. As energetic particles dissipate energy into the Martian atmosphere and regolith, they produce a host of secondary particles especially due to higher energy SEP events. These include neutrons, which can be highly biologically effective and therefore contribute a significant share of the dose equivalent. Of the particles that pass through the atmosphere the efficiency for the production of secondary neutrons is currently uncertain. During future missions, SEP intensities would most likely be forecasted and detected from the vantage point of space or Earth. Models must account for the details of SEP energy deposition into the atmosphere to assess the impact of these events on the surface of Mars. Hence, successful development of these models would require simultaneous, accurate measurements of the radiation field both in space and on the surface, such that the inputs and resulting outputs of the model system are fully constrained.

MSL is carrying the Radiation Assessment Detector (RAD), designed to assess radiation hazards from both neutrons and energetic charged particles on the surface of Mars. MSL has already begun and will continue to provide ground-truth measurements of the radiation environment on the surface of Mars, for both GCR and the SEP events over the course of the MSL mission (nominally 2 Earth years). These measurements are useful in providing necessary boundary conditions to constrain radiation exposure models primarily for GCRs, whose input flux, energy spectra, and variations are approximately uniform over much of the length of the solar system, but have never been measured on the Martian surface. MSL is also characterizing the contribution to the surface radiation environment of the SEP events that it samples. However, the impact of SEPs will not be fully characterized by MSL due to solar variability (few or no significant CMEs during the mission).

A discussion about the importance of the potential toxic effects of Martian surface materials is detailed in the NRC report, "Safe on Mars" (2002), by the Committee on Precursor Investigations Necessary to Support Human Operations on the Surface of Mars. They considered the presence and distribution of Cr(VI), commonly called "hexavalent cromium," especially important to understand because it is a strong human carcinogen. None of the past missions to Mars have carried instrumentation capable of measuring this species. The report also discusses other potential cancer-causing compounds, many of which are still of concern due to lack of sufficient data. Potential chronic effects like lung injury in the form of silicosis must also be studied in greater detail, preferably with a returned sample of Mars surface materials. Collection of data related to the investigations listed above was considered of highest priority from a risk perspective because the risk of insufficient data connects directly to the probability of loss of crew. In terms of impact on design, it was of comparatively less importance given the fact that the design of EVA systems, as well as dust mitigation protocols and design features, would already be at high levels, driven by other environmental challenges and forward and back contamination protocols.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
Medium	B3-1. Neutrons with directionality	B7.1: Measure neutrons with directionality. Energy range from ≤10 keV to ≥100 MeV.
Low	B3-2. Simultaneous spectra of solar energetic particles in space and in the surface	B7.2: Simultaneous with surface measurements, measure energy spectra in solar energetic particle events from orbit.
Medium	B3-4. Spectra of galactic cosmic rays on surface	B7.3: Identify charged particles at the surface from hydrogen to iron and measure particle energies from 10 MeV/nuc to 400 MeV/nuc along with LET measurement during solar min.
Low	B3-5. Toxicity of dust to crew	B7.4: Assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species (e.g., Cr(VI)) associated with dust-sized particles. Might require a sample returned to Earth as previous assays have not been conclusive enough to retire risk. B7.5: Fully characterize soluble ion distributions, reactions that

		occur upon humidification and released volatiles from samples from the surface and a depth that may be affected by human surface operations. Previous robotic assays (Phoenix) have not been conclusive enough to significantly mitigate this risk. B7.6: Analyze the shapes of Martian dust grains with a grain size distribution (1 to 500 microns) sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).

Objective C: Obtain knowledge of Mars sufficient to design and implement a human mission to the surface of either Phobos or Deimos with acceptable cost, risk and performance.

Priority note: The relative priority of Objective B and Objective C originate in political, or very high-level strategic, considerations, that are beyond the scope of this document. For the purposes of this document they should be interpreted as being of indistinguishable priority.

To achieve Objective C, the investigations in Objective A should be completed, plus the following:

Sub-objective C1: Understand the geological, compositional and geophysical properties of Phobos and/or Deimos sufficient to establish specific scientific objectives, operations planning, and any potentially available resources. (High Priority)

The primary science objective in the exploration of Phobos and Deimos relates to understanding the formation and origin of the Mars and moons (see Goal III: Sub-objective C1). This would lead to a certain set of scientific activities, including the deployment and operation of instruments, geological investigations, and the collection of samples. However, at present our understanding of Phobos and Deimos is insufficient to design the scientific aspects of a human mission, including selecting its landing site(s). In addition, a key question is whether resources exist on these bodies that may provide commodities required/desired. Detailed understanding of the presently unkown surface composition of Phobos will drive science and exploration objectives and may also influence systems designs.

Priority	P-SAG GFAs	MEPAG Investigations
High	C1-1. Surface composition	C1.1: Determine the elemental and mineralogical composition of the surface and near sub-surface of Phobos and Deimos. C1.2: Identify geologic units for science and exploration and materials for future in situ resource utilization operations.
Medium	C2-2. P/D Subsurface attributes	C1.3: Determine the first-order subsurface attributes of Phobos and Deimos. This could be done via measurement of gravitational field to a sufficiently high degree and order and/or by radar investigation.

Sub-objective C2: Understand the conditions at the surface and the low orbital environment for the Martian satellites sufficiently to be able to design an operations plan (including close proximity and surface interactions). (High Priority)

In addition to the geologic properties of the solid objects, it is important to understand the environmental conditions at the surface and the engineering conditions in a low orbit to be able to design the spacecraft systems adequately. In addition to the orbital particulate population (Sub-objective A2), we require knowledge of the electrostatic charging and plasma environment, a higher-order understanding of the gravitational field to yield efficient planning of proximity and surface operations, more complete knowledge of the regolith characteristics as required for operations planning and surface interaction, and detailed characterization of the thermal conditions as they relate to the vehicle, EVA and tool design.

Priority	P-SAG GFAs	MEPAG Investigations
Low	C2-1. P/D Electric and plasma environments	C2.1: Measure the electrostatic charge and plasma fields near the surface of Phobos and Deimos.
Medium	C2-2. P/D Gravitational field	C2.2: Determine the gravitational field to a sufficiently high degree to be able to carry out proximity orbital operations.
High	C2-3. P/D regolith properties	C2.3: Measure and characterize the physical properties and structure of regolith on Phobos and Deimos.
Low	C2-4. P/D thermal environment	C2.4: Measure the surface and subsurface temperature regime of Phobos and Deimos to constrain the range of thermal environments of these moons.

Objective D: Obtain knowledge of Mars sufficient to design and implement sustained human presence at the Martian surface with acceptable cost, risk and performance.

To achieve Objective D, the investigations in Objectives A and B should be completed, plus the following:

Sub-objective D1: Characterize potentially extractable water resources to support In Situ Resource Utilization (ISRU) for long-term human needs. (High Priority)

Key resources to support a long-term human stay at the Martian surface would include C, O, and H for both life support and ascent propellant (Drake 2009). For the purpose of this planning, it is assumed that information about ISRU related to extraction of resources from the atmosphere is discussed within Sub-objective B5, and it is not discussed further in this section. The most important additional resource need to support sustained human presence is water. Critical missing information is in two broad categories: (1). The location and attributes (e.g. concentration, depth) of the resource deposits of interest, and (2). The engineering information needed to be able to plan for the extraction/processing. This information is a central input into some very high-level architectural trades involving the mass, power, and risk associated with the equipment necessary to acquire and process these commodities from Martian resource deposits compared to the mass, power, and risk of simply delivering them from Earth.

In the case of hydrogen (or equivalently, water), ISRU has the potential to have a substantial impact on mission affordability (particularly as related to the amount of mass to be delivered to the surface), especially for long-stay missions. Information gathered from MGS, Mars Odyssey, MEx, MER, Phoenix, MRO and telescopic observations have shown that water exists on Mars in at least four settings: hydrated minerals in rocks and soils, in ground ice, in the polar ice caps (and perhaps in glaciers), and in the atmosphere. However, it is as-yet unknown whether the water in any of these locations constitutes a viable resource deposit, and whether the demands placed on the mission's processing system to extract the deposits would be compatible with the engineering, risk, and financial constraints of a human mission to Mars. Two classes of deposits are currently of highest interest:

Hydrated minerals: Numerous deposits of hydrated silicate and sulfate minerals have been identified on Mars from spectroscopic measurements [see Ehlmann et al. 2014 and references therein]. These deposits are attractive candidates for ISRU because: (1) they exist on the surface, thus their surface spatial distributions are easy to constrain using remote methods, (2) they exist in a variety of locations across the globe, thus provide many choices for mission landing sites, and (3) the low water activity in these minerals would preclude planetary protection issues. Limitations on existing measurements include: (1) uncertainty of volume abundance within the upper meter of the surface, (2) best available spatial resolution (~20 m/pixel) might not be sufficient for ISRU processing design, and (3) mechanical properties of H-bearing materials are not sufficiently constrained.

Subsurface ice: Accessible, extractable hydrogen is likely at most high-latitude sites in the form of subsurface ice [Boynton et al., 2002; Feldman et al. 2002; Mitrofanov et al. 2002]. In addition, theoretical models can predict subsurface ice in some mid-latitude regions, particularly on poleward facing slopes [Aharonson and Schorghofer, 2006]. Indeed, ice has been detected in high-resolution imaging and spetroscopy within fresh craters at northern latitudes as low as 42°. Based on observed sublimation rates and the color of these deposits, the ice is thought to be nearly pure with <1% debris concentration [Byrne et al. 2009]. Pure subsurface ice and other ice-cemented soil were also detected by the Phoenix mission [Smith et al., 2009]. Subsurface ice deposits have ISRU potential, but are ranked lower than deposits of hydrated minerals because: (1) low-latitude ice deposits are currently thought to exist only in glacial deposits that are associated with high elevations and difficult topography, and (2) mid-latitude deposits have substantial overburden that would make mining difficult (and in some cases are also in areas of difficult topography).

As is true of all extractive natural resources, determining whether a resource deposit is "ore" or "waste" cannot be determined without knowledge of *both* the resource and processing system. For the purpose of this planning document, the former requires information to be collected from flight missions to Mars (i.e. a resource exploration program), and the latter mostly or entirely requires engineering development on Earth (and thus is not described in this document). The resource exploration program is probably best organized into two sequential phases: Reconnaissance-scale characterization sufficent to make prioritization decisions (Phase I) and a detailed site-specific characterization sufficient to plan for specific mission design (Phase II). However, data from Mars may be needed to better constrain the excavatibility, overburden, and mission power/volume needs associated with specific H-resource deposit types.

The regolith is also a potential resource. In bulk form it could be used to cover habitats as radiation shielding, used for roads, and/or for other purposes. However, it is not currently believed that precursor investigations are needed in this area.

Priority	**P-SAG GFAs**	**MEPAG Investigations**
High	D1-4. Hydrated mineral occurrences	D1.1: Generate high spatial resolution maps (~2 m/pixel) of mineral composition and abundance. Verification of mineral volume abundance and physical properties within approximately the upper 3 meters of the surface. Mineral identification must also be verified.
Medium	D1-6. Shallow water ice occurrences	D1.2: Generate high spatial resolution maps (~100 m/pixel) of subsurface ice depth and concentration within approximately the upper 3 meters of the surface. Verification of ice volume abundance and physical properties within approximately the upper 3 meters of the surface.
Medium	D1-5. Shallow water ice composition and properties	D1.3: Measure the energy required to excavate/drill the H-bearing material. D1.4: Measure the energy required to extract water from the H-bearing material.
High	D1-3. Hydrated mineral compositions	D1.5: Measure the energy required to excavate/drill the H-bearing material. D1.6: Measure the energy required to extract water from the H-bearing material.

SECTION V. STRATEGIES FOR THE SCIENTIFIC EXPLORATION OF MARS

This section is still being revised. Comments are welcome on scope, structure, and content. The graphic is also still rough – it captures the desired concepts, but is not intuitional (suggestions?).

Analysis of the above Goals, Objectives, Sub-objectives, and Investigations enables the recognition of several strategies that could be used to guide the present and future exploration of Mars. These are identified in two ways:

(1) A strategy may define an overarching, high-level science pursuit that is not captured within any individual Goal, but that is sufficiently compelling to be a stand-alone pursuit. Ressults from this strategy may then feed into one or more Goals. For example, as will be discussed below, the study of habitability is a stand-alone (Mars) science pursuit. Additionally, science advances within Goal I will influence the definition of the larger-picture study of what it means for an environment to be habitable.

(2) A strategy may define a large-picture framework that clarifies how between-goal cross-cutting Investigations fit together, and where advancements within one Goal require advancements within other Goals. Not all cross-cutting Investigations yielded a strategy; we focus on those which could help the design of holistic mission(s) that incorporate investigations from multiple Goals. For example, as will be discussed below, Goals II and III have investigations that feed into Goal I Investigations; the interconnectedness of some of these studies is easily understood as relating to questions of habitability.

In summary, it is feasible that a strategy could connect goals "from the top" (over-arching; where Goal results feed into the strategy) or "from the bottom" (large-picture framework for cross-cutting Investigations); sometimes both. The strategies are listed below in no particular order, and their connection to the Goals is illustrated in **Fig. V-1**.

Historical Strategies

Follow the Water: In 2000-2001, at the time of the formation of MEPAG and the establishment of the first version of the Goals Document, it was recognized that water was a central aspect of many of the high-priority objectives and investigations in each of the four goals areas. MEPAG proposed this strategy as a means of simultaneously approaching multiple objectives, under all four goals. This strategy served as a very important focal point of the Mars program through the missions Mars Global Surveyor (MGS) (1996-2006), Mars Odyssey (ODY) (2001-present), Mars Exploration Rovers (MER) (2003-present), Mars Reconnaissance Orbiter (MRO) (2005-present), and Phoenix (PHX) (2007-2008). It is generally decided that our discoveries to date are sufficient to no longer warrant water as a primary focal point for the program; the 2008 Goals document (MEPAG, 2008) articulated the need to understand how the habitability of Mars evolved over geological time, from global to local scales. This has now emerged as an important stand-alone pursuit for Mars science – and, indeed, for planetary science in general.

Current Strategies

Understand the Long-Term Evolution of Habitability: Habitability is increasingly understood as a feature that emerges from and changes with the interaction of geological processes, climate and atmospheric evolution, and stellar evolution. This understanding informs and is informed by a growing set of observations of potentially habitable worlds both within and beyond our solar system. Mars is the most readily accessed planetary body (beyond Earth) where we can investigate, in considerable detail, how habitability has changed over time as a function of evolving geology, atmosphere, and climate. Indeed, the record available on Mars may actually preserve more extensive and detailed evidence of the early evolution of habitability than that available on Earth, potentially including a record of early chemistry and environmental context surrounding the origin of life.

To understand this evolution on Mars requires insights from geology- and climate-related investigations, as well as "snapshots" of local habitability, so that this area of focus cuts across Goals I, II, and III. In Goal I, the principal aim of characterizing habitability is to inform the selection of sites for subsequent life-detection missions. However, the environment-specific characterizations that result from such investigations also represent point observations, localized in time and space, that will aid in reconstructing how the habitability of Mars evolved through time.

Investigations within Goals II and III would also provide key insights in characterizing the evolution of habitability, including: characterize the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs; constrain evolution in the geological, geochemical, and photochemical processes that control atmospheric, surface, and shallow crustal chemistry, particularly as it bears on provision of chemical energy, and the availability of bioessential elements (abundance, mobilization, and recycling); constrain the nature and abundance of possible energy sources as a function of changing water availability, geophysical and geochemical evolution, and evolving atmospheric and surface conditions; evaluate the changing nature and magnitude of oxidative or radiation hazards at the surface and in the shallow crust.

Understand Mars as a System: At end of 2004, with extensive results from MGS, several years of data from ODY, and one year of data from the two MER rovers, it was recognized that Mars is significantly more diverse and complex than had been previously thought. Further missions and scientific studies have only emphasized that investigations into the primary components of the Martian system involve understanding how these components have interacted with each other during different epochs of Martian history. Thus, it is clear that to understand Mars requires that we understand Mars as a system, and that we need to understand the diversity of Mars, how that diversity originated, and the interconnectivity of the different components. The implication is that it is not generally possible to significantly advance one Goal to the exclusion of the others.

Goals II and III strongly feed into this strategy, as numerous high-level Mars science questions relevant for interpretation of the history of Mars involve interactions between the atmosphere and the (sub-)surface. For example, what were the environmental conditions on Ancient Mars and how are they recorded; and how does the volatile reservoir within the caps (and thus the atmosphere) change through obliquity cycles? Goal I also perhaps feeds into this strategy, as lifeforms would alter the conditions recorded (or present) wtihin the Martian climate and geology. Additionally, this framework of interconnectivity clarifies many of interdependecies between investigations within Goals I, II, and III; thus, this strategy also provides a "from the bottom" connection between all three Goals.

<u>*Utilize Mars Science to Enhance Comparative Planetology:*</u> This strategy focuses on efforts to understand important processes that also occur outside of Mars, and views Mars as one of many similar "bodies" (e.g., environment, planet, planetary system). As a well-studied, accessible rocky planetary body with a variety of information available over a range of spatial and temporal scales, Mars provides vital information about geologic processes relevant to planetary evolution and development of habitability. Atmospheric and surface processes can be studied under *Martian* conditions and then compared and contrasted with information about similar studies under terrestrial or other conditions. And to design a mission for sending humans to Mars, we need to know the ways in and degree to which Mars is similar (or not) to the environments humans generally exist within. Thus, this strategy provides a compelling larger-than-Mars framework for all four Goals.

While the comparison planetary body is commonly Earth, it can also be Venus (e.g., types of volcanism and how lava type and flow are influenced by planetary conditions), Titan (e.g., how do sand dunes move?), the Moon (e.g., how does impactor flux vary through the solar system?), or exoplanets (e.g., see Habitability). This "from the top", overarching strategy can be applied to a large number of compelling science questions, from "How does life start?" to "How can climate change occur and how extreme can it be?" to "How do planetary interiors evolve?"

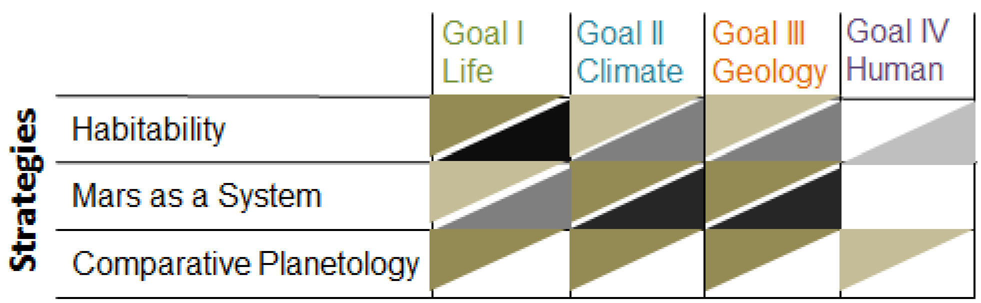

***Figure V-1**. Each of the exploration strategies identified here span at least 3 Goals. In each cell of this matrix, the upper-left half is filled if the connection between strategy and goal is "from the top" (i.e., results from the Goal feed into and influence definition of the strategy); the lower-right half is filled if the connection is "from the bottom" (i.e., if the strategy provides a framework for understanding cross-cutting investigations between the Goals). The darkness of the filling is related to the strength of the connection.*

<u>Engineering Advancements that Enable</u>

The Goals, Objectives, and Investigations indicate that our exploration of Mars would be enabled/enhanced by advancements in the following broad areas related to engineering development:

1) Global access--high and low latitudes, rough and smooth surfaces, low and high elevations, in addition to precision landing.

2) Access to the subsurface, from a meter to hundreds of meters, directly (e.g., drilling) and indirectly (e.g., geophysical sounding).
3) Access to time varying phenomena that would require the capability to make measurements over long periods (e.g., climate studies covering from one to several Martian years).
4) Access to microscopic scales with instruments capable of measuring chemical and isotopic compositions and determining mineralogy as well the ephemeral or continuous presence of liquid water on microscopic scales.
5) Planetary protection and sample handling that would involve implementation of cleaning methods, contamination control, sample acquisition and processing methods, and sample packaging/sealing for possible return to Earth.
6) Advanced instrumentation, especially in situ life detection and age dating.

Orbital and landed packages could make many of the high priority measurements, but others might require that samples be returned from Mars. As noted in other MEPAG and National Academy of Science reports, study of samples collected from known locations on Mars and from sites whose geological context has been determined from remote sensing measurements have the potential to significantly expand our understanding of Mars. A full discussion of these issues is beyond the scope of this document, but has been addressed by MEPAG science analysis groups, as well as by the 2013-2022 Planetary Sciences Decadal Survey (NRC, 2011).

Appendix

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App. 2: Acronyms used

To be added

App. 3: Goal I Supplemental Information

The specific approach and methods involved in any search for life beyond Earth depend critically on how the concepts of life, habitability, and biosignatures are conceived. Below, these concepts are discussed in specific reference to Mars exploration and the strategy outlined in this document.

Life

The NRC Committee on the Limits of Organic Life noted that the only unquestionably universal attribute of life is that it must exploit (and therefore requires) thermodynamic disequilibrium in the environment, in order to perpetuate its own state of disequilibrium. Beyond this absolute, the Committee cited a set of traits that it considered likely be common to all life[2]:

- It is chemical in essence, and most probably consists of interacting sets of molecules having covalently bonded atoms, including a diversity of “heteroatoms” (such as N, O, P, etc. in terrestrial organisms) that promote chemical reactivity.
- It probably requires a liquid solvent to support such molecular interactions.
- It probably employs a molecular system capable of Darwinian evolution.

Reference to the known characteristics of life on Earth can serve to add detail and constraint within each of these categories, but heavy reference to this single example carries the risk of “terracentricity” – a potential to overlook life that may be unlike our own. A key challenge for Mars astrobiology is thus to find a point of balance between the all-encompassing generality of the descriptions above and the specificity and concreteness that comes from reference to life on Earth. The NRC Committee on an Astrobiology Strategy for the Exploration of Mars developed a working set of characteristics of life (as quoted above) that reflects such a balance, and which serves as the basis for the approach outlined here. This approach generally corresponds to the following logic:

The relative similarity of Earth and Mars (in comparison to, for example, gas giants or icy moons) suggests that differences in life forms that originated independently on the two bodies would likely occur at a secondary, rather than first-order level. That is, notions of life that differ at the fundamental levels of biochemical scaffolding (alternatives to carbon) or required solvent (alternatives to water) require planetary conditions and chemistries that differ dramatically from those of either Earth or Mars. However, differences from terrestrial life become increasingly possible, and ultimately probable, with increasing levels of biochemical specificity. These considerations bear differently on the conceptualization of the habitability and life detection sub-objectives. For the most part, habitability relates to the core needs and attributes of life, so a presumed first-order similarity between terrestrial and Martian life allows terrestrial notions of habitability to be applied, with somewhat relaxed boundary conditions, to Mars. On the other hand, as developed in studies of terrestrial systems, biosignatures (especially organic molecular/ biosignatures) commonly represent extremely specific attributes of biochemistry (e.g., specific lipids or particular sequences of amino or nucleic acids), morphology, or process. While such specific markers of life would be unquestionably valuable if detected on Mars, the likelihood that the *same* markers (the same specific choices of biomolecules) would arise through an independent origin and elaboration of life seems low. Thus, while life detection strategies for Mars should ideally allow for the detection and characterization of Earth-like biosignatures, highest priority should be given to approaches and methods that define and seek biosignatures in a broader sense. Strategies for framing and applying concepts of habitability and biosignatures are addressed in greater detail below.

Prebiotic Chemistry

Even if life itself never existed on Mars, the planet could have hosted, and might still preserve evidence of, a pre-biotic chemistry. Identifying aspects of such chemistry on Mars would make an important contribution to our overall understanding of life as an emergent feature of planetary systems. Prebiotic chemistry can be conceived as the set of chemical processes – including chemical synthesis, non-genomic molecular evolution, and self-organization of structures and catalytic cycles – that collectively lead to the emergence of minimally functional life. Here, "minimal functionality" is assumed to be conferred by a compartmentalized, interacting set of molecular systems for (a) information storage; (b) catalytic function; and (c) energy transduction. Progress in understanding any of these processes would constitute an important contribution in the context of Goal I. However, the most tractable near-term focus may be to understand the processes – whether endogenous synthesis from simple molecules or delivery from exogenous sources – that supply basic biochemical building blocks, such as sugars, amino acids, and nucleobases, as well as comparable alternatives that are not used in present terrestrial living systems but might nonetheless play a role in an emerging biochemistry. More advanced stages of prebiotic chemistry – which could be viewed as partially complete representations of each of the main classes of biosignatures described below – could be difficult to discern from degraded remnants of living cells. The potential for confusing prebiotic chemicals or structures with degraded biosignatures emphasizes the importance of establishing multiple lines of evidence in definitively identifying life. In particular, finding evidence of extreme selectivity in isotopic composition or stereochemistry would be a strong indicator of life, rather than prebiotic chemistry. As with life itself, the emergence of prebiotic chemistry must be considered within the context and boundary conditions supplied by the physicochemical environment, and evidence of such chemistry will be subject to the same processes of degradation as evidence of life. Thus, investigations relating to prebiotic chemistry should be pursued within the framework and context provided by the habitability and preservation potential sub-objectives that are outlined above.

Defining and Quantifying Habitability

In the context of Mars science, habitability has thus far been defined (for example, in the NRC "An Astrobiology Strategy for the Exploration of Mars") as the potential of an environment to support life. Assessment of this potential has focused to a very large degree on determining whether liquid water was or is present in the environment in question. These constitute an inherently "binary" approach to habitability – liquid water was either present or was not; life could either be supported, or could not – that has served to identify a wide spectrum of apparently water-formed (nominally habitable) Mars environments. Reference to life on Earth – with habitats that exhibit a continuum from sparsely to densely inhabited – suggests that significant variation in habitability could likewise exist within the set of water-bearing environments on Mars. As described above, the main purpose of habitability sub-objectives A.1 and B.1 is to narrow and prioritize the search space for life detection efforts. Investigations and methodologies capable of resolving "more habitable" environments from "less habitable" ones should therefore be emphasized. A key challenge for the coming decades of Mars exploration is thus to augment the liquid water metric that has served as a guide to habitability with additional metrics that would aid in prioritizing sites for potential life detection missions. Although a consensus approach for characterizing "relative habitability" does not yet exist within the Mars community, it is clear that additional resolving power in any model would depend on the ability to resolve (by measurement or inference) variations in each of the parameters thought to underpin habitability:

- A solvent capable of supporting complex biochemistry. For terrestrial life, liquid water (above minimum chemical activity levels) is an absolute requirement.

- A source of energy to drive metabolism. Organisms on Earth require energy availability to meet discrete minimum flux and Gibbs energy requirements. Light (from the near infrared to visible range) and chemical energy are known to be utilized by life on Earth; the viability of alternative energy sources has yet to be sufficiently explored or validated.
- Raw materials for biosynthesis. All life on Earth requires the elements C, H, N, O, P, and S, and also variously requires many "micronutrients" (notably transition metals). Traditionally, these are collectively referred to as "bioessential elements". As applied in this document, this term refers primarily to C, N, O, P, and S.
- Sustained physicochemical (environmental) conditions that allow for the assembly, persistence, and function of complex structures and biomolecules (especially biopolymers, like proteins and nucleic acid polymers, whose backbones contain relatively labile bonds). Extremes of temperature, pH, radiation, and salinity can, individually or in combination, render an environment uninhabitable.

Given the working model and rationale described above, habitability shall be considered to correspond closely to the parameters known to constrain life on Earth. While environments that could be habitable for exotic organisms may be missed by this approach, it is appropriately conservative. Conditions that could support terrestrial life can be said to be definitively habitable. Some level of divergence from a strictly Earth-centric view of habitability can also be adopted by (a) focusing more on "core requirements" (e.g., water, carbon, and energy) than on requirements that underpin the more specific attributes of biochemistry (e.g., micronutrient requirements), and (b) allowing for the possibility, at least at a screening level, that Martian organisms might conceivably transcend the currently known physicochemical boundaries (e.g., the biologically tolerated temperature range) of life on Earth.

Whatever models emerge for resolving habitability may differ in parameterization of, and sensitivity to, each of these basic factors that underpin habitability. Yet all will be supported by an effort to constrain "degree" in reference to each parameter: how long liquid water was available, at what chemical activity level, and whether intermittently or continuously; how much energy was available, in what forms, and how fast it could have been delivered into a system; what concentrations or fluxes of bioessential elements were present, and what processes may have served to mobilize or cycle them; and, what range of temperature, pH, radiation level, and other relevant environmental parameters an environment may have experienced. All such measurements should be placed, to the greatest extent possible, within geological and environmental context.

While the ability to resolve almost any of these parameters would likely be greater with landed platforms and instruments, a key aspect of the proposed habitability sub-objectives is the capability of orbital measurements to yield several lines of "screening level" information, beyond evidence of liquid water. Of particular interest is the ability of combined morphological and mineralogical evidence to establish geological context and place screening-level constraints on possible energy sources and physicochemical regimes; and of trace gas and other measurements to infer conditions of formation in subsurface source regions. Such measurements should serve as a key initial step in resolving habitability among the variety of environment types that could be targeted for life-detection missions.

Biosignature types and contamination challenges

Biosignatures can be broadly organized into three categories: biomolecular, metabolic, and structural. Significantly, examples can be found of abiotic features or processes that bear similarity to biological features in each of these categories. However, biologically mediated processes are characterized by speed, selectivity, and a capability to invest energy into the catalysis of unfavorable processes or the handling of information. It is the imprint of these unique attributes that resolves clearly biogenic features within each of the three categories. Most of the biosignatures can be, to a certain degree, imitated by non-biological processes. Robust identification of traces of life therefore requires a variety of evidence, ideally from the following three categories.

1. Biomolecular. Life invests energy into the synthesis of complex structural, functional, and information-carrying molecules. Identifying terrestrial versions of these molecules (e.g., membrane lipids, proteins, and nucleic acid polymers, respectively) on Mars would aid in attributing a biological origin, but would likewise increase the importance of ruling out terrestrial contamination. Likewise, because these represent specific biochemical "choices," our search must allow for alternative possibilities. Accordingly, the methods employed should be as inclusive as possible with the broad spectrum of organic compounds, and should seek to capture information about structure, complexity, and organization. In synthesizing the suite of biomolecules that constitutes a functional organism, life also concentrates key elements (e.g., C, N, P, S, and various micronutrients, in terrestrial life) in stoichiometric ratios, and evidence of such co-occurring elements (particularly in organic form) should be sought. Finally, the enzymatic processes that synthesize biomolecules frequently also impose significant kinetic isotope fractionation effects and exhibit high stereochemical or enantiomeric selectivity. These additional layers of information within the basic organic chemistry should be sought when possible.

2. Metabolic. In constructing and maintaining itself, life extracts energy and material resources from its surroundings, and may leave unique overprints on the environment in the process. Photosynthetic energy harvesting is evident in light-absorption by pigments (for example, characteristic deep absorption features in the NIR to visible) and may confer on organisms an ability to build up significant redox disequilibrium in their surroundings (as with the strong oxidizing effect of oxygenic photosynthesis). Chemosynthetic metabolism extracts energy from chemical reactions that are thermodynamically favored to proceed even in the absence of life. Life distinguishes itself in these reactions by speed (catalysis 10^6-fold or greater, in many terrestrial examples) and selectivity (as expressed in kinetic isotope effects and, sometimes, stereoselectivity). Catalytic speed may be evident in progress toward equilibrium in chemical reactions that are abiotically sluggish under ambient conditions, concentration or depletion of specific elements or chemical species, or strong chemical gradients or zonation (including in redox and pH). The latter can sometimes be recorded in biomineralization, which may be an important class of evidence for ancient systems. Selectivity may be evident in isotopic fractionation between candidate substrate and product pairs (noting that abiotic processes may also fractionate), or in deposition of structurally or chemically distinctive mineral forms. Where possible, chemical information (e.g., analysis of potential metabolic product/reactant pairs) should be coupled with isotopic and other information, to capture combined evidence of life's catalytic and selective effects. An important aspect of the metabolic class of biosignatures is that, unlike biomolecular markers, life's role in imposing an imprint on the environment is simply catalytic. Hence, special allowance need not be made, in this category, for “alternative” or exotic biochemical machineries – it is the reactants and products of catalyzed reactions (and the imprints of speed and selectivity thereon) that constitute the biosignature, and not the catalyst (organism) itself.

3. Physical structures. Life imposes organization and order on its physical environment at many levels, from the structure and sub-structures within a cell to community-level structures formed by trillions of individuals (e.g., microbialites and microbial fabrics). The structural components, cells, colonies, biofilms, mats and extracellular polymeric substances (EPS), may be preserved in fossilized form in a number of ways. Cells may leave organic walled impressions, mineral-coated or impregnated structures, or empty casts in a mineral precipitate. Biofilms and mats may also be preserved as organic impressions in sediments or mineralized structures.

Cells walls can be preserved as organic impressions in fine-grained, anaerobic sediments. This kind of preservation can be aided by the fixation of metals, such as Fe, on cell envelopes, which may retard lysis. The most common form of preservation of microbial structures is mineral-assisted fossilization. In this process, minerals bind to the organic surfaces of the cells and/or their polymers in a passive reaction resulting in encrustation or permeation of the organic structure. The microbial surfaces and exopolymers therefore act as “mineralizing templates.” Depending upon the availability of the minerals in solution, the microorganisms may be completely entombed in a mineral precipitate. Many mineral phases can bind to microbial cell walls including silica, carbonates (Ca, MgCa, Fe, Mn), metal oxides/hydroxides (Fe/Mn and magnetite), sulfates (Ca, Sr, Ba, Fe), sulfides (Fe, Ni, Pb, Zn, CuFe), phosphates (Ca), clays, and zeolites. In anaerobic environments, the macromolecules can be entombed within the mineral precipitate. However, in order for the fossilised cells or cell comunities to be preserved in the rock record, the mineral-coated or permeated microbial structure needs to become encased in a mineral cement or by fine-grained sediments. Here, further diagenetic changes may take place, including changes in mineralogy (e.g. transformation of oxyhydroxides to oxides), replacement (complete or partial) of one mineral by another (e.g., silicification of carbonate mineralized remains), or dissolution. The final mineral or sediment-encased microbial fossils may exhibit different morphological preservation modes.

On a cautionary note, abiological mineral precipitates can be notoriously confused with fossilized microorganisms. Many minerals, for instance silica, may form simple spherical, oval, elongated and even twisted morphologies.

The problem of contamination: Any of the classes of biosignature evidence that might be sought to address sub-objectives A.3 and B.3 is potentially subject to contamination. However, this is perhaps most critical for the “biochemical” class, where any of a broad range of organic contaminants have potential to be introduced by the spacecraft itself. Experiments aimed at biochemical detection must therefore include appropriate controls against terrestrial contamination. To this end, new techniques and instruments are presently being developed for cleaning and monitoring of spacecraft contamination. In searching for life on Mars, sample handling and analytical procedures must include procedural blanks that allow for the tracking and quantification of contamination introduced by the spacecraft and its processes, for any analytes that might serve as evidence of life. Planning along these lines should also address the potential that the aging of a spacecraft, or its exposure to different environments, could alter its potential to introduce contamination over the course of a mission.

Preservation of features related to assessing habitability or biosignatures

Once an organism or community dies, its imprint on the environment, in any of the classes of features described above, begins to fade. Preservation/degradation of the different types of biosignatures is controlled by the combination of biological, chemical and physical factors, and a combination that would best preserve one class of features may not be favorable for another. *Characterization of the environmental features and processes on Mars that preserve specific lines of biosignature evidence is a critical prerequisite in the search for life.* Along with an assessment of relative habitability, assessment of preservation potential should serve as a key criterion in selecting sites for life detection missions.

It will be important to consider an environment's potential to preserve evidence in each of the three categories of biosignatures. Often, preservation within the biochemical category is given the most attention, because such molecules (in undegraded form) may present the most diagnostic evidence of life, but may also be among the most labile forms of evidence. However, obtaining clear evidence of life on Mars would likely require multiple biosignatures in different categories. Thus, recognizing physical structures in context, identifying associated biominerals, and finding the chemical and isotopic imprints of metabolism would be no less important. Studies of records of ancient communities on Earth might provide a preliminary guide for understanding preservation potential on Mars. However, it should be noted that the differing histories and surface environments of those two worlds may translate into quite significant differences in the processes that degrade or preserve specific lines of evidence. For example, metamorphic alteration represents a major destructive mechanism for biosignatures from early Earth environments, while exposure to ionizing radiation and oxidation may present the greater challenge to biosignatures on Mars, especially since they are difficult to study in the absence of sufficient terrestrial analogs.

Preservation of biochemical: Organic molecules in sediments are rapidly degraded in natural environments by a number of chemical and biological processes during early diagenesis and rock lithification, as well as during low temperature burial metamorphism to high temperature metamorphism (on Mars this will be equated with impact shock and/or volcanism). Chemical and radiolytic alteration and degradation on the surface of Mars would include the effects of ionizing radiation, radionuclide decay, oxidation in the presence of liquid water and certain minerals, such as Fe(III), and exposure to oxidants, such as H_2O_2. Such alteration could occur at any time following deposition in association with singular or multiple diagenetic events in addition to the period of exhumation and exposure at the surface. Furthermore, in the presence of liquid water, racemization of chiral organic molecules could occur within a couple of million years. *The ideal locality for searching for biomolecules on Mars would therefore be in the subsurface in materials that have not been exposed to liquid water since their burial and preservation.* Some diagenetic effects, such as molecular restructuring to yield resistant cross-linked aliphatic or aromatic macromolecules, or physical/chemical association with protective lithologies and mineral matrices, may improve the preservation of organic biosignatures. The stable isotopic composition of organic compounds is relatively well conserved, to the extent that basic molecular skeletons are preserved. On Earth, the effect of thermal metamorphism on organic matter is to degrade it chemically, typically forming isotopically lighter volatile species and isotopically heavier residual refractory solids.

Preservation of physical structures: On Earth, long-term preservation of physical microbial structures depends upon several factors, in particular the following. (1) The rapid burial of organic structures in anaerobic conditions by fine-grained impermeable siliceous sediments, such as clays, where they are protected from oxidizing fluids. This preserves the structures as flattened organic compressions between sediment layers. (2) Replacement or coating by a wide range of minerals. It must be noted that different microorganisms have different susceptibilities for mineral fossilization and those that are particularly delicate may not fossilize at all; thus, the microfossils preserved in a rock will not necessarily represent the original microbial community.

The preservation of larger scale biological constructs (such as biolaminated deposits or stromatolites) is aided by the association with sediments and carbonate precipitation on Earth. Such physical biosignatures may be mechanically destroyed by erosion (including impact erosion). As mineralogical structures, they can be corroded, for instance by acidic ground waters if they have a carbonate composition. The complicated post-diagenetic history of aqueous alteration of the sediments at Meridiani Planum is illustrative of the processes that could have affected potential Martian microbial structures if they were ever present. Changes to the rock encasing the physical structures brought about by different types of metamorphism (shock, thermal), will induce gradual destruction of the structures depending upon the degree of metamorphism. For example, Early Archean terrestrial rocks that have undergone little more than burial metamorphism (prehnite-pumpellyite to lowermost greenschist facies) contain well preserved physical biosignatures. Thus, over billion year geological time scales, physical biosignatures have the potential to be preserved on Mars as they are on Earth, assuming similar processes aid their preservation.

Preservation of biominerals: The range of minerals passively formed as a result of microbial metabolism is very large. As with fossilized microbial structures (as above), the preservation of biominerals will depend on the history of alteration (metamorphic, chemical, physical) of the rock after formation.

App. 4: Goal IV Supplemental Information

History of Goal IV Revisions

The 2013 revision was based on analysis conducted by the joint MEPAG-SBAG (Small Bodies Assessment Group) Precursor Strategy Analysis Group (P-SAG 2012). The P-SAG was chartered to update and prioritize what investigations are needed before the first human missions to the Martian system (as described in DRA 5.0). The P-SAG was also asked to consider implementation options and priorities as well as technology needs (which are not appropriate for inclusion in the MEPAG Goals document). The P-SAG report provides additional investigation details beyond those described here.

- Note that the P-SAG investigations relevant to human missions to Phobos/Deimos are not described here. Check the SBAG website for details (http://www.lpi.usra.edu/sbag/).

The 2010 revision of Goal IV was based on analysis conducted over a period of about four months between 2009-2010 by a committee lead by Lim et al. (see Goal IV text in MEPAG 2010[6]). It considered both (1) new scientific and exploration data about Mars and (2) planning information related to the Design Reference Architecture (DRA) 5.0 document (Drake, 2009). A considerable number of experts were consulted in the process of revising recommended sub-objectives and priorities.

- Objective A, which is organized into a prioritized list of sub-objectives, was updated. This structure is parallel to that of the objectives in Goals I, II, and III.
- Former Objective B was removed because it was inconsistent with the overall structure and purpose of the MEPAG Goals Document.
- Former Objective C, which relates to a set of atmospheric investigations, was merged with Sub-objective IVA. There was previously an unnecessarily high degree of overlap between the two.

A major revision of Goal IV was completed in 2005 (following the 2004 National Vision for Space Exploration and subsequent planning activities). The revision effort included the formation of two parallel MEPAG study teams (Beaty et al., 2005; Hinners et al., 2005). Each prepared reports that became the foundations for Goal IV Objective A (a prioritized listing of the sub-objectives and investigations necessary to safely and effectively carry out the first human mission to Mars), and Goal IV Objective B (a roadmap that demonstrated the technologies on the critical path to the first human mission), respectively. Established more recently, Objective C (critical atmospheric measurements that would reduce mission risk and enhance overall science return) was derived from an objective that was originally part of Goal II, but which seemed better suited for inclusion under the purview of Goal IV.

Investigations proposed to be retired in this (2015) Goal IV Version

MEPAG Sub-objective	P-SAG SKGs	MEPAG Investigation
B5 – Atmospheric ISRU	B6-3. Trace gas abundances	Measure the trace gas composition of the Martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU.
B6 – Landing Site and Hazards	B7-3. Trafficability	Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements.
B7 – Crew Health and Performance	B3-2. Simultaneous spectra of solar energetic particles in space and in the surface	Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in solar energetic particle events.
B7 – Crew Health and Performance	B3-4. Spectra of galactic cosmic rays on surface	Identification of charged particles at the surface from hydrogen to iron and measure particle energies from 10 MeV/nuc to 400 MeV/nuc along with LET measurement during solar min.

GFA B6.3 Measure the trace gas composition of the Martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU. Measurement of trace gassses in the Martian atmosphere by the SAM instrument of MSL has provided sufficient information about the well-mixed Martian atmosphere to provide information for the next stage of atmospheric ISRU investigations.

GFA B7.3 Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements. From investigations by the Viking and Phoenix Landers, and the rovers Pathfinder, Spirit, Opportunity, and Curiosity, we have a relatively good understanding of the a number of physical properties for wind-blown deposits and soils (such as rough size and shape distributions, density, cohesion, angle of internal friction, bearing strength, shear strength, and composition). From orbital and in situ measurements, we understand that the sulfate-rich salts in the soils constribute to their cohesiveness.

GFA B3.2 Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in solar energetic particle events. Measurements from instruments on Earth-based sattelites or those at other locations in the heliosphere made in conjunction with those on Mars' surface should be sufficient to measure estimated exposures from SEP events relevant to human exploration.

GFA B3.4 Identification of charged particles at the surface from hydrogen to iron and measure particle energies from 10 MeV/nuc to 400 MeV/nuc along with LET measurement during solar min. The RAD instrument at MSL has made measurements at the surface for over one Mars year of continuous data during the solar maximum. For the measurements of charged particles, RAD has measured from 14 MeV/nuc to 400 MeV/nuc for hydrogen to iron – but due to the close proximity of the RTG, which produces neutrons at 14 MeV energies below this are saturated. The detector for RAD is silicon, and has made measurements of LET with respect to Si, which can be converted to water – the standard LET measurement substance.

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***Table App. 4-1*: Mapping of MEPAG Goal IV to Mars Strategic Knowledge Gaps**

Partial listing of P-SAG Strategic Knowledge Gaps (SKG) and Gap-filling Activities (GFA). This table focuses on the Gap-filling Activities to be performed at Mars from P-SAG (2012). See the full P-SAG report and associated matrix for details, including technology demonstrations and investigations not requiring Mars flight opportunities.

We propose deleting the text highlighted in blue, if the Investigations are considered retired.

P-SAG		MEPAG		
SKG	**GFA**	**Sub-objective**	**Investigation**	**Priority**
A1. Upper Atmosphere	A1-1. Global temperature field	A1	A1-1	High
	A1-2. Global aerosol profiles and properties		A1-2	High
	A1-3. Global winds and wind profiles		A1-3	High
A3. Orbital Particulates	A3-1. Orbital particulate environment	A2	A2-1	Medium
B1. Lower Atmosphere	B1-1. Dust Climatology	B1	B1-1	High
	B1-2. Global surface pressure; local weather		B1-2	High
	B1-3. Surface winds		B1-3	High
	B1-4. EDL profiles		B1-4	Medium
	B1-5. Atmospheric Electricity conditions		B1-5; B1-6; B1-7	Low
B2. Back Contamination	B2-1. Biohazards	B2	B2-1	High
B5. Forward Contamination	B5-1. Identify and map special regions	B3	B3-1	High
B4. Dust Effects on Surface Systems	B4-1. Electricity	B4	B4-1; B4-2; B4-3	Low
	B4-2. Dust physical, chemical and electrical properties		B4-4	High
	B4-3. Regolith physical properties and structure		B4-5; B4-6	Medium
B6. Atmospheric ISRU	B6-1. Dust physical, chemical and electrical properties	B5	B5-1	High
	B6-2. Dust column abundances		B5-2	Low
	~~B6-3. Trace gas abundances~~		~~B5-3~~	Low
	NEW		B5-4	High
B7. Landing Site and Hazards	B7-1. Regolith physical properties and structure	B6	B6-1; B6-2	Medium
	B7-2. Landing site selection		B6-3	Medium
	B7-3. Trafficability		~~B6-4~~; B6-5	Low
B3. Crew Health & Performance	B3-1. Neutrons with directionality	B7	B7-1	Medium
	~~B3-2. Simultaneous spectra of solar energetic particles in space and in the surface~~		~~B7-2~~	Low
	~~B3-4. Spectra of galactic cosmic rays on~~		~~B7-3~~	Medium

	~~surface~~			
	B3-5. Toxicity of dust to crew		B7-4; B7-5; B7-6	Low
C1. Phobos/ Deimos Surface science	C1-1. Surface composition	C1	C1-1	High
	C2-2. P/D Gravitational field		C1-2	Medium
C2. Phobos/ Deimos Surface operations	C2-1. P/D Electric and plasma environments	C2	C2-1	Low
	C2-2. P/D Gravitational field		C2-2	Medium
	C2-3. P/D regolith properties		C2-3	High
	C2-4. P/D thermal environment		C2-4	Low
D1. Water Resources	D1-3. Hydrated mineral compositions	D1	D1-1; D1-2	High
	D1-4. Hydrated mineral occurrences		D1-3	High
	D1-5. Shallow water ice composition and properties		D1-4; D1-5	Medium
	D1-6. Shallow water ice occurrences		D1-6	Medium