# Mars Science Goals, Objectives, Investigations, and Priorities: 2018 Version

## Mars Exploration Program Analysis Group (MEPAG)

### Finalized and Published online: October 1, 2018

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Recommended bibliographic citation:
MEPAG (2018), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2018. D. Banfield, ed., 81 p. white paper posted October, 2018 by the Mars Exploration Program Analysis Group (MEPAG) at https://mepag.jpl.nasa.gov/reports.cfm.

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# PREAMBLE

NASA's Mars Exploration Program (MEP) has requested that the Mars Exploration Program Analysis Group (MEPAG) maintain what is colloqually referred to as the Goals Document, first released in 2001 (MEPAG 2001), as a statement of the Mars exploration community's consensus regarding its scientific priorities for investigations to be carried out by 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 roughly every two to three years (MEPAG 2004; 2005; 2006; 2008; 2010; 2012, 2015, and this document[1]). The 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. A separate, unrelated process for forward planning that is similar in some ways to the Goals document is the National Academies of Sciences, Engineering, Medicine (NASEM) Decadal Survey, which is carried out once every 10 years. MEPAG's Goals Document constitutes one of many inputs into the NASEM 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. The Goals are organized around major areas of scientific knowledge; 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 knowledge, strategies, and milestones needed to achieve the Goal. The Sub-objective tier 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 constitute the final tier of the hierarchy. Although some Investigations could be achieved with a single measurement, others require a suite of measurements, some of which require 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 by this document, 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 complete. 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.

Finally, this updated hierarchy has been augmented with Goal-specific spreadsheets that show

[1] All MEPAG Goals Documents can be found at https://mepag.jpl.nasa.gov/reports.cfm?expand=science.

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[2] (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 and accuracy
- 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, the order of Investigations does not imply they need to be undertaken in sequence, 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 "Section V: Cross-cutting Strategies". In the 2015 version of the Goals Document, we identified overarching connections between the Goals, as well as connections to compelling, larger-than-Mars science questions, within a re-worked final chapter "Integrating the Goals to Understand Mars and Beyond" (this chapter is also in the 2018 version).

We also identify "cross-cutting Investigations" 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). These Investigations are identified in the high-level overview spreadsheet that accompanies this document as Supplementary Material. 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. The list of cross-cutting Investigations is meant to be thorough, but is not expected to be complete.

[2] The summary spreadsheet can also be found at http://mepag.jpl.nasa.gov/reports.cfm.

**Additional notes relating to the 2015 version of the Goals Document (as the 2018 text was unchanged outside of Goals II A-B and III A)**

New results from ongoing missions at Mars (Mars Science Laboratory (MSL), Mars Reconnaissance Orbiter (MRO), Mars Express (MEx), the Mars Exploration Rover (MER) *Opportunity*, and 2001 Mars Odyssey) were a primary impetus for the 2015 cycle of revisions and re-assessment of priorities that will help guide the MEP forward into the decade of the Mars-2020 mission and beyond. In the 2015 revision of the Goals Document, Goals I-III received substantial revisions based on published scientific results and a major summary[3] of many aspects of Mars science presented at The Eighth International Conference on Mars, held at Caltech in July, 2014. Additionally, although that conference was an 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)[4] and into a structure more consistent with the other Goals.

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: Dave Des Marais (Life), Rich Zurek (Climate), Phil Christensen (Geology), and Marcello Coradini (Preparation for Human Exploration).

**Additional notes relating to the 2018 version of the Goals Document**

The 2018 version of the MEPAG Goals document includes changes from the 2015 document, only within Goals II (Objectives A-B) & III (Objective A). These updates were undertaken in response to an identified disconnect between the forefront questions in the Mars Polar Science community and those discussed in the 2015 version of the MEPAG Goals Document, under to climate and geology. The disconnect was originally brought to MEPAG's attention through a report produced from a broadly attended 2016 meeting of the Mars Polar Science community[5]. The MEPAG Goals Committee determined that the disconnect warranted revisions to the Goals Document, and in consultation with the Polar Science Community and eventually the full Mars community, the current version of the document was produced. Because this was only a partial revision to the Goals Document, we did not re-prioritize Sub-Objectives or Investigations in Goals II or III, but rather left new or modified ones with the same priorities as their predecessors in the 2015 document. We anticipate undertaking a full MEPAG Goals Document revision (including priorities) in late 2019 following the Ninth International Conference on Mars[6].

[3] http://www.hou.usra.edu/meetings/8thmars2014/presentations/
[4] http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf
[5] https://www.hou.usra.edu/meetings/marspolar2016/, Conference report presented to MEPAG at Meeting 35: https://mepag.jpl.nasa.gov/meetings.cfm?expand=m35
[6] https://www.hou.usra.edu/meetings/ninthmars2019/

| Section of the Goals Document | Updated in this doc | Prev. Signif. Update |
|---|---|---|
| Goal I: Determine If Mars Ever Supported Life | 2015 | 2010 |
| Goal II: Understanding the Processes and History of Climate on Mars | **2018 (this document)** | 2015 |
| Goal III: Understand the Origin and Evolution of Mars as a Geological System | **2018 (this document)** | 2015 |
| Goal IV: Prepare for Human Exploration | 2015 | 2012 |
| Integrating the Goals to Understand Mars and Beyond | 2015 | N/A (the previous incarnation, *Section V*, was updated in 2010) |

**Major organizers and contributers to previous versions:**

*The current and all previous versions of the MEPAG Goals document are posted on the MEPAG website at: http://mepag.jpl.nasa.gov/reports.cfm.*

2015 version: Victoria E. Hamilton, Tori Hoehler, Jennifer Eigenbrode, Scot Rafkin, Paul Withers, Steve Ruff, R. Aileen Yingst, Darlene Lim, and Ryan Whitley

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 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 and MEPAG Goals Committee

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

2001 Version: Ron Greeley and MEPAG Goals Committee

# GOAL I: DETERMINE IF MARS EVER SUPPORTED LIFE

| Objectives | Sub-objectives |
|---|---|
| **A.** Determine if environments having high potential for prior habitability and preservation of biosignatures contain evidence of **past life**. | **A1.** Identify environments that were habitable in the past, and characterize conditions and processes that may have influenced the degree or nature of habitability therein. |
| | **A2.** Assess the potential of conditions and processes to have influenced preservation or degradation of biosignatures and evidence of habitability, from the time of formation to the time of observation. Identify specific deposits and subsequent geological conditions that have high potential to have preserved individual or multiple types of biosignatures. |
| | **A3.** Determine if biosignatures of a prior ecosystem are present. |
| **B.** Determine if environments with high potential for current habitability and expression of biosignatures contain evidence of **extant life**. | **B1.** Identify environments that are presently habitable, and characterize conditions and processes that may influence the nature or degree of habitability therein. |
| | **B2.** Assess the potential of specific conditions and processes to affect the expression 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 (MEP). 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 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 (NRC 2007) assumed that hypothetical Martian life forms would exhibit the following characteristics (quoting verbatim):

- They [Martian life forms] 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 (i.e., electron transfer 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 and Extant Life

The strategies, technologies, target environments, and forms of evidence involved in a search for extant life are sufficiently distinct from those involved in a search for past life that they are delineated into separate objectives. Here, "extant" refers to life that is metabolically active or that could become metabolically active under favorable conditions, whereas "past" refers to any life that does not meet this criterion. It must be acknowledged that dormant but viable organisms (e.g., bacterial spores) represent a grey area in the extant/past distinction: such organisms are clearly "extant" life, but might be sought using strategies or approaches from both extant and past life investigations. Despite the potential overlap in this specific case, the extant/past distinction is clear enough overall to provide a useful basis of organization in Goal 1.

**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., whether conditions and processes that define the environment are supportive or obstructive to life and over what timescales, and
b) biosignature preservation potential, i.e., the conditions and processes during deposition, diagenesis, burial, and exhumation that 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 Appendix 3. 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 yes-or-no 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 because they occur on Earth: e.g., aqueous, thermal, and barometric diagenesis; chemical and biological oxidation; physical destruction by mechanical fragmentation, abrasion, and dissolution; and protection by minerals (i.e., inclusions, surface bonding, grain boundaries). 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 Appendix 3.

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 lifeforms. 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 Appendix 3.

## Prioritization

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 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.

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. 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 environments having high potential for prior habitability and preservation of biosignatures contain evidence of past life.

**Sub-objective A1: Identify environments that were habitable in the past, and characterize conditions and processes that may have influenced the degree or nature of habitability therein.**

Investigations in this Sub-objective 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 past 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 conditions, 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 the time of formation to the time of observation. Identify specific deposits and subsequent geological**

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

Investigation A2.1: Identify conditions and processes that would have 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 effects of regolith and rock burial on the shielding from ionizing radiation); the prevalence, extent, and type of metamorphism; and potential processes that influence isotopic or stereochemical (i.e., the spatial arrangement of atoms in molecules) information.

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

Investigation A2.3: Characterize the conditions and processes that would have 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 biosignatures of a prior ecosystem 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 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 environments with high potential for current habitability and expression of biosignatures contain evidence of extant life.

### Sub-objective B1: Identify environments that are presently habitable, and characterize conditions and processes that may influence the nature or degree of habitability therein.

Investigations in this Sub-objective should be applied to each environment (surface or subsurface) under investigation in order to support comparisons in habitability characteristics. Investigations here are focused (and priorities based) on the information needed to fully characterize habitability in such environments without reference to the current ability to obtain 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 conditions and processes to affect the expression 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 processes such as 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 (e.g., in the form of rapid catalysis of chemically sluggish reactions, stable isotopic fractionation, and/or strong chemical gradients), or potential biogenic gases that 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 climate record of the recent past that is expressed in geological, glaciological, and mineralogical features of the polar regions. |
| | **B3.** Determine the record of the climate of the recent past that is expressed in geological and mineralogical features of low- and mid-latitudes. |
| **C.** Characterize Mars' **ancient** climate and underlying processes. | **C1.** Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present. |
| | **C2.** Find physical and chemical records of past climates and factors that affect climate. |
| | **C3.** Determine present escape rates of key species and constrain the processes that control them. |

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. There is also considerable interest in understanding how Mars' climate fits into the context of other planetary atmospheres, including Earth's.

Mars' climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile and aerosol reservoirs, evaluated from diurnal to geologic time scales. The climate history of Mars can be divided into three different states: *(i)* Present climate, operating under the current obliquity and observable today; *(ii)* Past climate operating under similar pressures, temperatures, and composition, but over a range of orbital variations (primarily obliquity) that change the pattern of solar radiation on the planet and whose effects are evident in the geologically recent physical record; 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 was likely episodically or continuously stable on the surface.

**Prioritization**

On Mars, as on Earth, 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. Because 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. Furthermore, since not all climate processes leave a distinctive record, it is also necessary to determine which climate processes will have left detectable signatures in the climate archives of the recent past**.** Numerical models play a critical role in interpreting the recent past and ancient climate, and it is imperative that they be validated against observations of the present climate in order to provide confidence in results for more ancient climates that are no longer directly observable.

Based on this philosophy, the Climate Goal is organized around three Objectives, each pertaining to the different climate epochs. Investigations within a Sub-objective are assigned a prioritization of 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 within lower priority Objective C could be on par with or more important than a lower priority Investigation within the higher priority Objective B.

## 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 maintain and drive the present climate of Mars. The boundary between the lower and upper atmosphere is an imprecise concept. The mesopause, around 90 km, provides a convenient choice. Below it, chemical composition is relatively stable and visible and infrared (IR) wavelengths dominate radiative heating. Above it, and particularly above the homopause around 110 km, chemical composition is more variable and ultraviolet (UV) and shorter wavelengths dominate radiative heating.

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, particularly when combined with data assimilation techniques, 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; better diurnal coverage and better 3-D distributions are needed. 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, and volatile phase changes) to the forcing over daily, seasonal, and multi-annual timescales. As such, characterization of the thermal and dynamical state of the lower atmosphere (temperatures and winds) is a necessary, but not a sufficient, element of this Sub-Objective.

Obtaining a high quality data set from a properly accommodated weather station (i.e., one in which thermal and mechanical contamination from 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 demonstrate the impact of accommodation on the fidelity of the measurements. Once high quality surface measurements of basic meteorological parameters have been acquired, measurements of quantities that have been poorly or never measured generally should 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 orbital missions have provided a good climatological record of global scale column dust, water, and ice opacity. Mars exhibits a vertical dust structure more complex than originally thought. The bulk, global thermal structure also has been captured over multiple years. Nonetheless, these orbital measurements are substantially limited in their local time coverage and over the poles. Due to these limitations, diurnal variations and atmospheric behavior in polar regions are poorly constrained**.** Moreover, nadir measurements generally have been limited to vertical resolutions of about a scale height, and off-nadir or limb sounding measurements generally have 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, and by improving the vertical resolution of temperature, dust, water vapor, and dust profiles. New measurements, such as remotely-derived wind velocity would also advance the Sub-objective. Therefore, future orbital measurements that are motivated by this Sub-objective should provide new measurements (e.g., wind) or significantly improve spatial and temporal coverage and resolution beyond the existing data and ideally should 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 (convectively unstable) temperature gradient.

The scientific results of this Sub-objective have substantial relevance to engineering aspects of the 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 (usually 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 by observations, especially at the local- and lander scale. 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 Strategic Knowledge Gaps (SKG) (P-SAG 2012) for entry, descent and landing (EDL) operations, which benefits the entire MEP, and facilitates achievement of every MEPAG 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 longer timescales and on all spatial scales from turbulent to global. 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 and 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 high quality wind measurements at the surface, made simultaneously with temperature and pressure, remain a high priority. New and novel measurements generally are considered to be of higher priority than those that would 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 result in 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 full diversity of Martian geography and topography are required (e.g., plains vs. craters vs. 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. The annual polar condensation and sublimation cycle causes ~1/3 of the current atmospheric mass to transfer between the surface and the atmosphere. This annual cycle drives both global and regional transport processes. Measurement of noncondensable tracers (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.

At all scales, better diurnal coverage is needed in order to capture ephemeral phenomena, as well as systems (such as dust storms) that evolve over timescales of less than a day.

<u>Investigation A1.2:</u> Characterize dust and other aerosols, water vapor and carbon dioxide and their clouds in the lower atmosphere (High Priority).

Dust and clouds ($H_2O$ and $CO_2$) 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 clouds, although the record is problematic over the poles and is based on a narrow window of local times. Spatial and temporal variations in the vertical distribution are less well characterized. Orbital observations demonstrate that the vertical distribution of dust can be complex in space and time and the processes leading to the complex distributions are uncertain. Vertical water vapor distributions are relatively unknown, but probably exhibit similar complex structures. Moreover, the radiative forcing from dust, ices, and water vapor depends not only on their vertical distributions, but also their optical properties**.** Characterization of dust, water vapor, and clouds may be decomposed into four areas:

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

Although additional column abundance information is welcome, significant 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 aerosols, 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.

Important sources and sinks for these materials exist in surface reservoirs, including polar caps and polar layered deposits (PLD). The fluxes of these materials into and out of these regions are important.

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 and into the lower atmosphere is essential to interpreting the observed behavior of the atmosphere near the surface and in the planetary boundary layer (PBL). The surface budget is composed 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. To date**,** 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 (momentum) 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. Although this information is important, it is of lesser priority than the other two areas in this Investigation.

**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 not been well 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.

Achieving this Sub-objective requires measurements of the densities, velocities, and temperatures of neutral and ionized species in the upper atmosphere, as well as measurements of the dominant forcings (e.g., solar irradiance, coupling to the lower atmosphere, conditions in the solar wind and magnetosphere).

<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. Because ionized species in the upper atmosphere generally are 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*

Orbital observations 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 had 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 on numerous occasions by radio occultation instruments, yet these data cover only a limited range of local times. They also have been measured extensively by 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.

<u>Investigation A2.2:</u> Measure temperatures of neutral and ionized species in the upper atmosphere (Medium Priority).

The Martian upper atmosphere thermal structure is poorly constrained due to a limited number of measurements at selected locations, seasons, and periods scattered throughout the solar cycle. Temperatures of ions and electrons have not been measured at a significant level. 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. Because temperatures are controlled by the solar extreme UV (EUV: 5-110 nm) 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.

<u>Investigation A2.3:</u> Measure the forcings that control the dynamics and thermal structure of the upper atmosphere (Medium Priority).

Measurements 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. Relevant measurements are valuable only if they are acquired simultaneously with measurements of the state of the upper atmosphere. These forcing mechanisms 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. Over both a 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 can be significant (up to factors of ~2 to 10).

<u>Investigation A2.4:</u> 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*

Direct measurements of the velocities of neutral and ionized species in the upper atmosphere are needed. 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. Such velocity measurements should have a vertical resolution of one neutral scale height and a lateral resolution commensurate with the spatial scale of the crustal magnetic field.

**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, $CH_4$, $SO_2$, the hydroxyl radical OH, the major ionospheric species) is not yet sufficient to provide a detailed understanding of the atmospheric chemistry of Mars.

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. For example, in the lower atmosphere recent in situ measurements of O by MSL strongly suggest an unknown or unaccounted for process is operating. Also, the importance of electrochemical effects, which may be notably significant for certain species (e.g., $H_2O_2$), and of chemical interactions between the surface and the atmosphere, has 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.

Advances in 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 diurnal cycle, solar cycle, seasons, and dust storms. Temporal coverage must match the species and processes in question. Relatively well-mixed and slow reacting species may only require sporadic measurements, commensurate with the expected chemical lifetime. Other highly reactive species may require sampling at greater than diurnal frequencies.

Investigation A3.1: Measure globally the vertical profiles of key chemical species (High Priority):

- *Neutral species including $H_2O$, $CO_2$, CO, $O_2$, $O_3$, $CH_4$, 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 A3.2: 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 $H_2O$, HDO, OH, $CO_2$, O, $O_2$, $O_3$, $SO_2$, $CH_4$, $H_2CO$, $CH_3OH$, $C_2H_6$.*

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 horizontal spatial and temporal variability of sources and sinks. By tracking species with different photochemical lifetimes, information on atmospheric transport can also be extracted.

Investigation A3.3: 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 (Medium 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) generally is considered a prerequisite to this Investigation.

Investigation A3.4: Measure key electrochemical species (Low Priority).

Electrochemical 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 seasonal polar caps, and the Polar Layered Deposits (PLD), and how these reservoirs influence or record the present climate. The seasonal polar caps play a major role in these exchanges.

Knowledge of the processes that control the lifting of dust from the surface and into the atmosphere is 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. Furthermore, rapid pressure changes associated with dust devils and electrostatic forces also may be important. In the south polar region, dust injection by seasonal $CO_2$ jets may be significant.

Investigation A4.1: Characterize the fluxes and sources 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 and 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, measurements 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 of the turbulent fluxes along with 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. Other processes may lift dust in polar regions, including seasonal $CO_2$ jets and avalanches on margins of the PLD.

Charging of dust and sand grains due to collisions and the resulting electric 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 processes exchanging volatiles and dust between surface and atmospheric reservoirs have affected the present horizontal and vertical distribution of surface and subsurface water and $CO_2$ ice (Low Priority).

Water ice has been detected at many locations and depths. At mid- and high-latitudes, water ice may be stored within pores or as bulk ice beneath a lag deposit. In the PLD, water ice may be exposed on the surface of steep scarps. $CO_2$ ice is stored at and beneath the surface of the south polar layered deposit. The current distribution of these materials is not in equilibrium with the environment, which suggests that they were emplaced under different climatic conditions.

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 after the $CO_2$ sublimes in spring. Mechanisms of deposition (falling “snow” or direct condensation) as well as metamorphosis 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 mid- and high-latitudes in both hemispheres and may buffer long-term surface-atmosphere exchange because protective layers of water-ice (for the $CO_2$ units in the south PLD) or dust lags (for bulk ice at mid-latitudes) allow these units to persist through obliquity changes. The current equilibrium state between the subsurface water ice and the atmosphere is unknown, as is how that equilibrium state has changed over time. Assessment of net accumulation or loss of the residual ice deposits and mass, density and volume of the seasonal ice as a function of location and time are important components of this Sub-objective. The transport of carbon dioxide may also be variable if $CO_2$ condensed in large-scale sub-surface reservoirs, such as the buried deposits discovered near the south pole, can exchange with the atmosphere.

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

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 record primarily 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. The processes that shape the PLD, and their relative importance, are not well-known. This impedes efforts to infer the climate history from the records contained within the PLD. Thus, better characterization of processes now operating on the formation, removal or change in layers is germane to this Investigation.

Investigation A4.3: Determine the energy and mass balance of the surface volatile reservoir over relevant timescales, and characterize their fluxes (Low Priority).

The annual cycling of atmospheric $CO_2$ into and out of the seasonal caps is a primary driving force of the Martian climate. The seasonal caps are primarily $CO_2$ ice with the addition of small amounts of water ice and dust that act as condensation nuclei and persist after the $CO_2$ sublimates.

The seasonal caps may reach a maximum depth of 1 to 2 m, but spatial and seasonal variability in thickness and density (or column abundance) is only partially constrained. Observations of seasonal and diurnal deposition of volatiles bears directly on the surface-atmosphere interface, exchange of energy and mass between the surface and atmosphere, and the thermal state of atmosphere. The amount, rate, and distribution of deposition and sublimation is determined by the balance of several energy sources and sinks, including insolation, net radiative loss to space, the latent heat of fusion, summertime heat storage in the regolith, and atmospheric storage and transport of energy.

The seasonal cap persists for many months during the polar night, but at its lowest latitudes the cap experiences diurnal forcings that cause its margin to be highly variable, even dissipating during the day to return at night. Similar processes occur throughout the year at high elevations on the volcanoes. Due to poor local time coverage in existing observations, a result of sun-synchronous spacecraft orbits, existing observations have not been able to measure this variability.

To satisfy this investigation fully, it is necessary to determine the distribution of $H_2O$ and $CO_2$ frost deposition and loss on diurnal, seasonal, and multi-annual timescales via precipitation, direct deposition, and sublimation, from within the seasonal cap down to the lowest latitudinal extent.

In terms of the permanent caps and the PLD, knowledge about the rates of energy flux and mass accumulation on diurnal and seasonal time scales is very limited. Debates continue on whether the PLD are gaining or losing mass. The energy-mass balance is intimately related to the question of what happens at the surface with energy absorption/reflection and volatile phase changes, especially sublimation, direct deposition, and precipitation that reaches the surface. By constraining these properties, at best through in situ measurements, it will be possible to begin to answer bigger questions of how much ice is gained or lost each year and what the long-term trends are.

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

As Mars' obliquity varied in the geologically recent past, volatiles would have transferred between the atmosphere and reservoirs in the surface and sub-surface, thereby changing the mass of the atmosphere and redistributing materials across the surface. 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 that has been discovered buried near the south pole. Changes in the atmospheric mass due to partial atmospheric collapse of $CO_2$ onto the surface would have affected the thermal structure and dynamics of the atmosphere in myriad ways. For instance, $CO_2$ ice may cover large portions of the polar regions, and water-ice may be redistributed from the poles to the equator or mid-latitudes. In those cases, the planetary albedo would have been different and the changed surface pressure would have altered the efficiency of dust lifting. Because $CO_2$ condenses under different conditions than other atmospheric species, even the atmospheric composition will have varied through time**.**

Many geological features that formed in the recent past are available for interpretation today. Their properties likely contain information about the climate under which they formed. This information about the climate of the recent past can be used to test predicted extrapolations from the current climate. Such tests against the recent past are essential validation for extrapolating further back in time, when Mars was likely more habitable than today. The most likely locations of preserved records of recent Mars climate history are contained within the north and south polar layered deposits **(**PLD**)** and circumpolar materials. The PLD and residual ice caps may reflect the last few hundred thousand to few tens of millions of years, whereas terrain softening, periglacial features, and glacial ice sheets at mid- to equatorial-latitudes may reflect high obliquity cycles within the last few tens to hundreds of millions of 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 climate archives corresponding to this period. The Sub-objectives described below include 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, or on how volatiles have shifted between the atmosphere and surface and sub-surface reservoirs due to obliquity and other possible changes. A discovery of volatile reservoirs changes assumptions about how much volatiles have been available and which processes need to be considered (e.g. different surface pressure conditions).

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 MSL 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 PLD 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 PLD or other gas-preserving ices.

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

Terrestrial ice cores have provided invaluable information from isotopic measurements about the ages of terrestrial ice and about the climatic history of Earth, including glacial and inter-glacial cycles. Similar information is likely present in ice deposits on Mars. As on Earth, volatiles on Mars fractionate due to multiple factors. For gas species in the atmosphere, molecular weight and freezing point determine what is incorporated into the surface deposits. For isotopes, loss to space, sublimation from a surface deposit, and deposition onto the surface fractionate individual species. Thus, layers in the PLD will record compositional and isotopic variability. Measurements of isotopes within deposits of different ages, especially deuterium to hydrogen (D/H) will help to determine mass loss of water through time and the processes that are recorded during layer formation.

Investigation B1.2: Determine how and when the buried $CO_2$ ice reservoirs at the south pole formed (Medium Priority)

Greater than one atmospheric mass of $CO_2$ is stored beneath the south polar residual cap. This ice accumulated in three periods, but the processes and timing that led to partial atmospheric collapse and sequestration are not known. Nor is it understood why only three periods are represented. No $CO_2$ reservoir currently exists at the north pole, but evidence of past $CO_2$ glaciation may exist there. Determining the enabling processes and epochs under which these deposits formed will provide valuable information about recent changes in the Martian climate.

**Sub-objective B2: Determine the climate record of the recent past that is expressed in geological, glaciological, and mineralogical 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. In particular, it is unclear how materials are sequestered and maintained through large-scale climatic changes.

Extensive layered deposits in the polar regions composed primarily of water ice with measurable portions of dust and $CO_2$ ice are not in equilibrium with their surroundings. This suggests that these deposits were thermodynamically stable at some point in the climate of the recent past. However, interpreted records in the polar regions of mass lost and subsequently re-deposited indicate that frequent and significant changes in the stability of these deposits have occurred. Clues to the evolution and periodicities of the climate are recorded in the stratigraphy of the PLD, including its physical and chemical properties. Specific examples of the type of information these deposits may preserve include a stratigraphic record of volatile mass balance; insolation; atmospheric composition, including isotopic 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). Critically important is to understand the processes by which the PLD were produced and the processes recorded in the properties of the PLD**.**

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: Determine the vertical and horizontal variations of composition and physical properties of the materials forming the Polar Layered Deposits (PLD) (Medium Priority).

The stratigraphy of the PLD contains a long record of accumulation of dust, water ice, and salts. These materials vary horizontally across the PLD likely due to local variations in conditions and latitudinal variations in insolation and dynamics. They vary vertically due to temporal variations in their rates of accumulation and removal. Each process of accumulation may have left a stamp that can be measured by examining exposed outcrops from orbit with optical and radar instruments and in situ by sampling the subsurface with instruments that measure composition.

Unconformities indicate local or cap-wide removal of ice, likely due to transport to other locations. This may be indicative of regional or global climate change. Trapped gases in each layer should provide information about the composition of the atmosphere at the times of layer formation and any subsequent modification. Salts in the ice as portions of the crystalline structure may provide additional information about atmospheric aerosol re-distribution and mineral sources.

Investigation B2.2: Determine the absolute ages of the layers of the Polar Layered Deposits (PLD) (Medium Priority).

Knowledge of the ages of individual layers of the PLD, including the important lowermost layers, will provide firm constraints for climate models and for the recent history of Martian climate. Techniques that can determine the ages include isotopic measurements and interpretation of stratigraphy. Additionally, determination of the rates of relevant processes may provide independent constraints on layer ages.

Investigation B2.3: Determine which atmospheric and surface processes are recorded during layer formation (Medium Priority).

The extent to which physical, chemical, and isotopic properties of the PLD are influenced by specific processes that occur at the PLD are poorly understood. For instance, the abundance of dust in a particular layer indicates the deposition rate of dust at the time of layer formation, but is also influenced by the acceptance of dust into the crystalline ice structure. In order to constrain climate history from in situ PLD measurements, it is necessary to understand more fully how layers are formed in the PLD. Direct extended observations of accumulation and loss of materials at the surface of the PLD are required.

Investigation B2.4: Constrain Mars' polar and global climate history by characterizing and interpreting the relationships between orbitally forced climate parameters and the layer properties of the PLD (Medium Priority).

Once the processes that influence the PLD are well understood, fundamental atmospheric properties in climate models, such as atmospheric mass, can be varied such that predicted PLD properties best reproduce observations. Agreement between observations and predictions will constrain the absolute ages of specific layers in the PLD.

However, current models do not reproduce a long-lived south PLD or mid-latitude ice. Until models can reproduce key features seen in the current climate, efforts to use such models to infer climate history will face substantial obstacles.

**Sub-objective B3: Determine the record of the climate of the recent past that is expressed in geological and mineralogical 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. Moreover, recent orbital observations have found substantial ice deposits at mid-latitudes. These features, interpreted to be glacial and periglacial 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 and for determining what climate processes influenced the geologic record.

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

<u>Investigation B3.1:</u> Characterize the locations, composition, and structure of low and mid-latitude ice and volatile reservoirs at the surface and near-surface (Medium Priority).

A variety of lines of evidence (direct imaging, spectral observations, neutron spectroscopy, radar observations) have indicated that sub-surface ice deposits exist at low and mid-latitudes. However, the locations, composition, and structure of these volatile reservoirs have not been determined. It is not clear whether these reservoirs are localized or were once part of a larger-scale glacial feature. Since these volatiles are potentially available for exchange with the atmosphere on geologically short timescales, these reservoirs could represent an important part of the atmosphere system.

<u>Investigation B3.2</u>: Determine the conditions under which low- and mid-latitude volatile reservoirs accumulated and persisted until the present day, and ascertain their relative and absolute ages (Medium Priority).

Volatile reservoirs at low and mid-latitudes may not be stable on geologically short timescales, depending upon their depth or latitude. Hence the presence and persistence of these features requires explanation.

Changes in Martian orbital parameters, including obliquity and $L_S$ of perihelion, are likely to influence the stability of these reservoirs. As obliquity changes, for example, ice deposits may shift between polar regions, mid-latitudes, and the tropics. This will affect global climate as planetary albedo and volatile availability also change. Therefore determination of the ages of known ice deposits will constrain the recent history of Mars' climate.

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

There is strong evidence that the ancient climate of Mars was very different from the present climate and likely more habitable as well. 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 existed 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 interpretation 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. All models rely on physical parameterizations and should be tested, where appropriate, against similar processes occurring on Mars now.

**Sub-objective C1: 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 and isotopic analyses of Martian samples, either on Earth or in situ.

<u>Investigation C1.1:</u> Measure the composition and 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.

**Sub-objective C2: Find and interpret 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.

Addressing 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.

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

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

Investigation C2.3: 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 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. Because 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.

Addressing 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.

Investigation C3.1: Measure spatial and temporal variations in the escape rates of key species (Low 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 importance of these diverse pathways is 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 C3.2: Measure the forcings that drive escape processes (Low Priority).

This Investigation requires essentially the same measurements as Investigation A2.3. However, here the motivation is to understand escape *processes* whereas in Investigation A2.3 the motivation is to understand how forcing mechanisms control the *current thermal and dynamical state* of the upper atmosphere.

# 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 investigate the processes that have created and modified that record. | **A1:** Identify and characterize past and present geologic environments and processes relevant to the crust. |
| | **A2:** Determine the absolute and relative ages of geologic units and events through Martian history. |
| | **A3:** Identify and characterize processes that are actively shaping the present-day surface of Mars. |
| | **A4:** 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 the Earth. There are compelling scientific motivations for the study of the surface and interior of the planet in its own right. Earth-like (or nearly Earth-like) environments — that is, environments similar to those on modern Earth — are rare in the history of the Solar System, and Mars represents a planet where such an environment once may have existed. Additionally, as we explore the outer Solar System, environments dominated by volatile cycles have been found that may share more similarities in surface-atmosphere interactions and resultant surface changes with Mars than with the Earth, and thus studies of Mars geology may contribute towards new types of comparative planetology investigations focused on the ways in which Mars is distinctly not like the Earth. 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.

## Prioritization

Within Objectives A and B, individual Objectives, Sub-objectives and Investigations were examined through the lens of understanding Earth-like environments (which includes understanding how Mars is not Earth-like), 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 planning over 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 science-value Investigation may be prioritized lower than another Investigation because its accomplishment is less likely within the timeline 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.

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).

Within each hierarchy level (Objective, Sub-objective, Investigation), the listed order corresponds to the prioritization: e.g., A is of higher priority than B, A1 is of higher priority than A2, and A1.1 is of higher priority than A1.2. However, prioritization is less obvious when moving between hierarchy levels; e.g., it is possible that a high priority Investigation within lower priority Objective B could be on par with or more important than a lower priority Investigation within the higher priority Objective A.

## Objective A: Document the geologic record preserved in the crust and investigate the processes that have created and modified that record.

The Martian crust contains a 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, $CO_2$, and other volatiles in all their forms; regions likely to have been habitable; processes involved in surface-atmosphere interactions; and the planet's thermal history. To understand that record requires interpretation of both present-day changes and observed (sometimes evolving, sometimes relict) landforms and structures, within a context of assumed environmental conditions and processes. 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 and including bedrock, regolith, and icy deposits.

### 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. Moreover, 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 depositional 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 Earth-like 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., Recurring Slope Lineae/RSL). This Investigation requires knowledge of the ages (see Sub-objective 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 data 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.

Investigation A1.2: 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 and their rates 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 also may 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 and such measurements should continue so as to cover more of the Martian surface. Furthermore, orbital data are critically enhanced by in situ determination of mineralogy, which ensures that the interpretations based on orbital data are correct and facilitates identification of species that either have limited spatial extent or concentration, or which cannot be detected in remote observations.

Investigation A1.3: Characterize the textural and morphologic features of rocks and outcrops.

Observations of unobscured (i.e., low dust level) rock surfaces 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 (hand lens scale) provide key indicators of rock-forming and -altering environments, including evidence for past Earth-like 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. High-resolution imaging across a range of scales, ideally in color and stereo, is required. Imaging in stereo or from multiple perspectives is particularly desirable to yield three-dimensional characteristics.

Investigation A1.4: Identify ice-related processes and characterize when and how they have modified the Martian surface.

Water and carbon dioxide frosts and ices on Mars (and the geologic evidence they leave behind) may be studied as an important indicator of changes in the Martian climate because they drive surface-modifying processes (such as frost heave, gully formation, $CO_2$ jets, loading on slopes). Additionally, they serve as reservoirs for volatiles, so recognizing the extent of ice at the poles and other surface and near surface locations (e.g., pore filling ice and massive ice at mid-latitudes) is key to evaluating the volatile budget. Understanding the processes and environmental conditions under which ice deposits form is important for evaluating how that volatile distribution may have changed throughout Martian history. A range of techniques can be applied to this Investigation, for example, active sub-surface radar or seismic sounding, neutron and other spectroscopies, radar, thermal and visible imaging, and subsurface ice collection and characterization. This Investigation has significant overlap with Investigations in Goal II, Objective B because of the geological and climatic nature of volatile deposits.

Investigation A1.5: 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 shaped dramatically 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 minerals. The study of igneous processes requires orbital and surface measurements of composition, morphology, and other aspects across a range of resolutions.

Investigation A1.6: Determine the processes that create dust and distribute it around the planet, identify its sources, and fully characterize its composition and properties.

Dust is a ubiquitous feature of the surface and atmosphere of Mars and an important window into the weathering and alteration history of the planet. However the genesis and fate of dust are poorly constrained, and questions remain about its composition. This investigation aims to understand the physical and chemical processes that make and alter dust. Also important is to identify the sites of dust creation and the mechanisms of transport and distribution across the planet. Critical open questions relate to the dust size distribution and if any process cements dust to form new geologic units. Additionally, knowing the average dust composition on the planet may aid in measuring the ages of layers in the PLD.

Investigation A1.7: Evaluate the effect of large- and small-scale impacts on the nature and evolution of the Martian crust and establish their production rates.

Impacts are one of the global processes shaping the crust and surface of Mars. Ubiquitous throughout most of the Solar System, some impact structures on Mars have unique characteristics 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 absolute and relative 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 Earth-like 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 in situ and/or returned sample isotopic analysis.

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

For decades, impact craters have 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 via comprehensive and topical geologic mapping.

Comprehensive geologic mapping is an 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. Special purpose or topical geologic maps (e.g., for landing site characterization) are produced in advance of more comprehensive mapping, typically when time critical information is required. Many areas of Mars are mapped at high resolution and are well-understood, whereas for others this is less true – 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 and data products. These various datasets must be linked by common cartographic standards to enable accurate correlation.

**Sub-objective A3: Identify and characterize processes that are actively shaping the present-day surface of Mars.**

Investigation A3.1: Identify present-day changes within the rocky or icy surfaces of Mars, and estimate past and present rates of change.

Over the past decade, many new examples of contemporary large- and small-scale changes have been identified within the coherent and granular rocky surfaces and polar ice surfaces of Mars – including, but not limited to:

- Mass-wasting (e.g., gullies on rocky and sandy slopes, linear gullies on sandy slopes, boulder tracks, avalanches at the PLD margins),
- Decadal-timescale or faster creation/evolution of erosional landforms (e.g., spiders),
- Migration and evolution of aeolian landforms (e.g., ripples and dunes),
- Changes within the polar cap surface features (e.g., Swiss-cheese terrain, PLD texture, and other polar cap pit features),
- New impact craters, and
- Rapid, localized changes in surface albedo that then fade over a season or multiple Mars years (e.g., RSL, slope streaks, and large-scale albedo changes in response to dust storms).

The many observed present-day surface changes have altered thinking about dominant Martian surface processes within at least the present Martian climate, and in some cases, observations have enabled a more robust test of hypothesized past surface processes. Continued investigations are needed to identify additional types of present-day changes, measure their rates, and constrain the timing and environment associated with these changes. Additionally, measuring the rate of activity and the variations in these rates between seasons or Martian years is important for extrapolating the effect of these surface changes over longer timescales (see Investigations A3.3 and A4.2). This investigation generally relies upon having overlapping spatial coverage in images and a sufficient temporal baseline and coverage for identifying whether an observed change occurs only within a particular season or Mars year.

Investigation A3.2: Determine relevant surface and atmospheric environmental conditions and/or processes that cause observable surficial changes over diurnal, seasonal, and multi-annual timescales.

Within the present Martian climate, the main processes that are currently known to generate diurnal-to-seasonal-to-decadal observable landform changes on Mars are related to *(1)* impacts, *(2)* diurnal and seasonal frost ($H_2O$ and $CO_2$), *(3)* wind, and *(4)* thermal stresses. The specific ways in which these drivers leave records on the Martian surface is becoming better understood as we identify yet more types of changes, connect them to specific environmental conditions, and also better understand and appreciate ways in which the Martian environment is not Earth-like. Independent observations of the present climate and environment, from multiple instruments or investigations, can constrain the relevant conditions for surface changes. This investigation relies upon the information (and related datasets) obtained from Investigation A3.1, coupled with observations of the environment where the activity is occurring, and possibly coupled with modeling and laboratory investigations of potential processes.

Investigation A3.3: Extend the evolving knowledge of active surface processes to other locations on the planet and backward in time.

Direct evidence of active surface processes on Mars is, in many cases, limited because of incomplete coverage of key datasets (e.g., overlapping high resolution images). Thus, it becomes necessary to extrapolate existing knowledge of active surface processes to places where comparable conditions may be present (now or in the recent past). This can be done by determining where else a given process may act or by locating similar features in regions where the environment is less-well known. In that way, the related new and relict features can be used as markers of specific present-day or recent environmental conditions across a larger portion of the planet than can be observed with current exploration techniques. Furthermore, extrapolating present rates of activity backward in time can yield constraints on the interpretation of older terrains (i.e., *the present is the key to the past)*. This investigation is about the broader application of our evolving knowledge of active surfaces processes; Investigation A4.2 is related through its focus on interpreting the processes recorded within both geomorphic markers and the rock record. This investigation can encompass a wide range of spacecraft observations (including images) and generally will involve the integration of different analyses and overlapping datasets collected around the globe.

**Sub-objective A4: Constrain the magnitude, nature, timing, and origin of past planet-wide climate change.**

Investigation A4.1: Identify paleoclimate indicators in the geologic record and estimate the climate 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 Martian climate over time. Relative timing and duration of different climate regimes can be estimated in some cases 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 composition, morphology, and subsurface characterization are needed for this Investigation.

*[We note that investigations of more recent climate change are addressed within Goal II, Objective B, which have cross-linkages with some investigations in Goal III, Objective A.]*

Investigation A4.2: Characterize surface-atmosphere interactions as recorded by aeolian, glacial/periglacial, fluvial, lacustrine, 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 A4.3: Determine the present state, 3-dimensional distribution, and cycling of water on Mars, including the cryosphere and possible deep aquifers.

Water is an important agent for modifying and generating geologic units 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 Investigation encompasses many possible measurements across all scales, with impact excavated ice and perhaps recurrent slope lineae as recent examples of manifestations of water in the current environment.

## 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-style activity 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 Earth-like planet, as plate tectonics-style activity (whether similar to that on Earth or unique to Mars) 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 is required to fully understand the distribution and intensity of current tectonic activity. This would be possible through a long-term, continuously active seismic network composed of multiple stations, or a single station supported by alternative means for locating seismic events.

**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. Accurate localization of seismic activity is necessary to fully address all objectives, for example, using at least four stations operating simultaneously for a full Mars year. However, progress in this Investigation could be made with a single station. InSight for example, a Discovery Program mission landing in 2018, will apply 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 the highest priority within this Objective.

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 coming from 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 moons' origin(s). 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 full interpretation of existing (or similar to existing) composition data and other observations, especially with regards to determining the moons' origin(s). Determination of this geologic history will depend on a range of data sets, including but not limited to identification and classification of geologic units based on spectral and morphological data, stratigraphic ordering, and crater age dating.

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

The compositions of Mars' moons promises to be the clearest discriminator between origin theories (especially when coupled with morphological data and interpreted within a geologic history, see Investigation C1.1). 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 to enable them to be associated with distinct morphologic units.

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

Models of the orbits of Mars' 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). This information could, for example, be determined from subsurface radar (of sufficient penetration depth and resolution) or high-resolution gravity maps.

**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 also of interest to Goal IV: Investigation A2.1). 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. A global crater size/density counting down to 100-m diameter would the most useful, so as to (1) normalize out any hemispherical asymmetries (e.g., due the moons being tidally locked or leading vs. trailing hemispheres), and (2) identify underrepresented crater-populations (due to downslope movement of material preferentially erasing smaller craters). All craters down to 250 m are thought to have been identified on Phobos, and many craters >150 m on Deimos have been identified, but image coverage is incomplete and was commonly acquired under sub-optimal lighting conditions.

# 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 & aerobreaking for human-scale missions at Mars. |
| | **A2.** Determine the orbital particulate environment in high Mars orbit that may impact the delivery of cargo & 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, Descent, & 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, 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. |
| | **B3.** Determine the Martian environmental niches that meet the definition of "Special Region." |
| | **B4.** Understand the resilience of atmospheric In Situ Resource Utilization (ISRU) processing systems to variations in Martian near-surface environmental conditions. |
| | **B5.** Assess landing site-related hazards, including those related to safe landing and safe operations (including trafficability) within the possible area to be accessed by elements of a human mission. |
| | **B6.** Assess risks to crew health & performance by characterizing in detail the ionizing radiation environment at the Martian surface and determining the possible toxic effects of Martian dust on humans. |
| | **B7.** 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. |
| **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 ISRU for long-term human needs. |

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, which allows 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 simply engineering against the problem. This set of issues was most recently considered by P-SAG (2012), who proposed the set of investigations that flowed into the 2012 version of the MEPAG Goals Document.

It is also worth noting 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, by computer modeling, and from 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. Connectivity between these various precursor activities is not maintained in this document.

## Changes to Goal IV since 2012

The 2012 version of Goal IV benefitted from integration of the work conducted by the Precursor SAG (P-SAG 2012). There has not been a subsequent re-evaluation of those priorities. 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. MSL carried two sensors that were directly in support of Goal IV: the Radiation Assessment Detector (RAD)[7], and Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)[8]. 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 continues to collect data of relevance (including from RAD). In addition, the Mars Reconnaissance Orbiter (MRO) has continued collecting data since 2012. Of particular significance to Goal IV are new results from atmospheric and geology instruments.

In sum, as of 2015 we can take partial to full credit for several of the Investigations described in the 2012 version of the Goals Document. In the 2015 version of Goal IV, this has resulted in the retiring of three previously described Investigations as close enough to complete, the adding of three new investigations that better characterize the remaining gaps, 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. The studies demonstrate that the key Objectives and Investigations should be

[7] Technical details on RAD can be found at http://mars.jpl.nasa.gov/msl/mission/instruments/radiationdetectors/rad/
[8] Technical details on MEDLI can be found at http://mars.jpl.nasa.gov/msl/mission/instruments/atmossensors/medli/

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 recent NASA-published concept for a human Mars mission is the Design Reference Architecture (DRA) 5.0 (Drake 2009). Based on this document, major revisions of Goal IV were made in 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, 2014[9]. 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). The primary strategy that differs from DRA 5.0 is the preference for a single landing site for a series of human surface missions. This strategy puts greater emphasis on connecting sustained human presence to the first human landings. The re-prioritization of the investigations outlined in Goal IV reflects this change in emphasis. However, all of the gap-filling activities remain the same and the re-prioritization conducted in the major revision of 2010 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 although there are many architectural choices available to conduct a given mission type, the precursor investigations required to execute a given type of human Mars missions is largely constant, 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.

For the purposes of Goal IV and in the context of a logical sequence to 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+ (sustained presence), and Goal IV- P/D (human missions to Phobos/Deimos). In this 2015 revision, we are updating this terminology and placing it into a more conventional, Objective-oriented 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 Objectives B, C, and D, because it is necessary to interact with the Martian upper atmospheric and orbital

[9] http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf

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.*

*These relationships also define a time series.* The precursor knowledge related to Objective A is the foundation for all other pathways; it is thus deemed of paramount strategic importance. The precursor information needed for Objectives B and C currently cannot 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, because Objective D would need to happen after Objective B, it has lower time-urgency, and it is therefore listed fourth in priority among the precursor objectives.

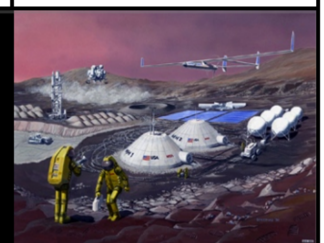
| **Objective A** | **Objective B** | **Objective C** | **Objective D** |
|---|---|---|---|
|  |  |  |  |
| Human missions to Mars orbit as a precursor to Mars surface missions (optional). | Human missions to the Martian surface. | Human missions to Phobos and/or Deimos as a precursor to Mars surface 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.*

In setting the priorities for Goal IV, these timing matters were considered, along with the P-SAG priorities. Gap-filling activities (GFAs) needed earlier are given higher priority than those needed later. (In Appendix 4, Table App. 4-1 maps the P-SAG priorities and timing into the priorities in this document.) In this chapter, assignment of a Sub-objective to a priority level is based on the highest priority GFA/Investigation within that Sub-objective.

P-SAG (2012) based its 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 priority levels are:

- High: Enables a critical need or mitigates 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 to Mars orbit 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 would provide a combination of mission-enabling observations and a reduction in the risk of loss of crew. Specifically, these data would reduce the risk of loss of crew and loss of mission primarily by reducing the risk associated with aerocapture and aerobraking. The level of acceptable risk is much lower for crewed 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.

One of the biggest challenges in conducting aerodynamic maneuvering, which includes both aerocapture and entry sequences, is the ability to slow the spacecraft sufficiently due to the very low density of the Martian atmosphere. To that end, recent analysis has suggested that Supersonic Retro-Propulsion (SRP) is a viable mitigating technique to aid in dynamical control of the spacecraft. Although the use of propulsion helps guard against potentially hazardous atmospheric unknowns, the atmospheric properties in the current database have large error bars and thus require significant fuel reserves to lower overall risk. Thus, although wind knowledge is not as critical with SRP (Investigation A1.3), atmospheric knowledge of temperature (to calculate density; Investigation A1.1) remains a high priority.

The Investigations listed in this Sub-objective include characterizing the variability on diurnal, seasonal and inter-annual scales from ground to >80 km in both ambient and various dust storm conditions. The observations are to directly support engineering design and also 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. The length of record specified in the Investigations is what is needed beyond the currently available data sets (i.e., as of MY 32). It is not possible to construct an empirical model that will completely retire the aerobraking/aerocapture strategic knowledge gaps associated with atmospheric uncertainty. Since empirical climatologies are necessary but not sufficient, a major focus of future investigations should be to acquire the data necessary to validate and improve the numerical models that provide atmospheric data at the spatial and temporal resolution relevant to spacecraft performance and operation.

Investigation A1.1: At all local times, make long-term (>5 Martian years) observations of the global atmospheric temperature field (both the climatology and the weather variability) from the surface to an altitude ~80 km with ~5 km vertical resolution (High Priority).

Atmospheric temperatures would provide the density information necessary to determine entry trajectories, atmospheric heating, and deceleration rates.

Investigation A1.2: At all local times, make long-term (>5 Martian years) global measurements of the vertical profile of aerosols (dust and water ice) 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 Priority).

Aerosol information is key to understand and validate numerical models of the temperature observations, and to understand and model the performance of guidance systems (especially optical systems).

Investigation A1.3: Make long-term (>5 Martian years) observations of global winds and wind direction with a precision ≤5 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. The record needs to include a planetary scale dust event. (Medium Priority)

A better understanding of winds would help allow pinpoint landing of surface systems. In addition, there are essentially no global measurements of the winds, a key component of the dynamical atmospheric system. Thus wind measurements will provide an important constraint on numerical models. Winds are expected to change dramatically (along with the temperature structure and aerosol distribution) during a planetary scale dust event, thus the winds under these conditions form an important part of the overall wind record.

**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).**

Investigation A2.1: Determine the spatial variation in size-frequency distribution of Phobos/ Deimos ejecta particles in Mars orbit (Medium Priority).

There may be a dust ring between Phobos and Deimos located in and around the equatorial plane of Mars. 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.

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

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 and B7 are of medium and low priority, respectively.

*To achieve Objective B, the Investigations in Objective A should be completed, along with the following:*

**Sub-objective B1: Determine the aspects of the atmospheric state that affect Entry, Descent, and Landing (EDL) design and 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 to validate atmospheric numerical models. The latter are essential to help characterize the potential dispersion of parameters. Existing recent observations fulfill some of the investigation requirements, but are currently insufficient to provide the necessary fidelity for the engineering models. 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 also too short and only exist at four locations. Thus, numerical models must be used to fill the gaps, and enough data of sufficient quality and resolution must be gathered so that we can have confidence that the numerical models are doing an adequate simulation of the EDL environment.

As with Sub-objective A1, these Investigations are global in nature and for similar reasons. As above, they provide context and validation for numerical models that provide vertical profiles of atmospheric properties relevant to EDL. By sampling a larger range of environmental conditions, extended global and local time coverage makes it more likely that the numerical models will capture those events most likely to be hazardous to spacecraft flying through the Mars atmosphere. Investigations B1.1-5 focus primarily on reducing risk for EDL. Investigation B1.6 focuses on risks to spacecraft in the Martian atmosphere.

We have not reached agreement on the minimum number of necessary atmospheric measurements (described below), 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, a few entry profiles, and mostly from inadequately validated atmospheric models. 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. The length of record needed is specified as that to be acquired beyond the current data sets (i.e., as of MY 32). Again, a prime consideration as to which data should be acquired is how that data can be used to improve and validate the numerical models that will be used to design and assess EDL/aerocapture hardware and operations.

As with Sub-objective A1, recent analysis has suggested that Supersonic Retro-Propulsion (SRP) is a viable mitigating technique to aid in dynamical control of the spacecraft. Thus, although wind knowledge is not as critical with SRP (Investigation B1.4), atmospheric knowledge of temperature (Investigation B1.3) is still a high priority.

Investigation B1.1: Globally monitor the dust and aerosol activity, especially large dust events, to create a long-term dust activity climatology (>10 Martian years) capturing the frequency of all events (including small ones) and defining the duration, horizontal extent, and evolution of extreme events (High Priority).

The dust activity climatology 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). Almost all current global atmospheric data sets are limited (by technique) under extreme aerosol conditions (such as planetary scale dust events). Accurately measuring these conditions is critical to understanding the structure, and dynamical behavior of extreme weather on Mars.

Investigation B1.2: Monitor surface pressure and near surface meteorology over various temporal scales (diurnal, seasonal, annual), and if possible in more than one locale (High Priority).

Surface pressure directly controls the total atmospheric mass and thus the altitude of critical events during EDL. For surface pressure, characterize the seasonal cycle, the diurnal cycle (including tidal phenomena) and quantify the weather perturbations (especially due to dust storms). The measurements would need to be continuous with a full diurnal sampling rate >0.01 Hz and a precision of $10^{-2}$ Pa.

Surface and near-surface meteorology provides information on the Martian boundary layer. They provide key parameters for the near surface atmosphere encountered at touchdown and launch as well as critical validation of Martian numerical boundary layer schemes. The surface is where energy, mass and dust are exchanged between the atmosphere and the surface and where a large part of the forcing of the atmosphere is located. In order to validate the atmospheric models it is vital to get the near-surface meteorology correct. Surface and near-surface meteorology includes simultaneous in situ measurements (temperature, surface winds and relative humidity) and high vertical resolution profiles of temperature and aerosol below ~10 km. To avoid constraining future destinations, multiple locations need to be sampled to provide adequate understanding of and confidence in modeling the impacts of local and regional effects on the meteorology under varying conditions.

Investigation B1.3: Make temperature and aerosol profile observations under dusty conditions (including within the core of a global dust storm) from the surface to 20 km (40 km in a great dust storm) with a vertical resolution of <5 km (High Priority).

Global temperature profiles are a key measurement to reduce EDL risk associated with the large error bars associated with unknowns in density variation.

Investigation B1.4: Profile the near-surface winds (<15 km) with a precision ≤2 m/s in representative regions (e.g., plains, up/down wind of topography, canyons), simultaneous with the global wind observations. 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 Priority)

A better understanding of winds would help allow pinpoint landing of surface systems. The winds are also a very sensitive diagnostic for the validation of numerical boundary layer models.

Investigation B1.5: Obtain temperature profiles (to calculate density) from all landed missions with vertical resolutions of at least 1 km between the surface and 20 km. It is desired to have a higher resolution in this near-surface altitude range to reduce the future risk of the highly dynamic events that occur during this phase of EDL (Medium Priority).

Even though several robotic missions to Mars surface have successfully entered the atmosphere and landed, the measurements made during a given EDL only provide a thin slice through the atmosphere at a single instant in time.

Investigation B1.6: 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 (Low Priority).

Atmospheric electricity 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, Ascent 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 represent a hazard during surface operations, as they could effect static-discharge of sensitive equipment, communications, or frictional charging interactions ("triboelectricity") between EVA suits, rovers, and habitats. Understanding the ground and atmospheric conductivity, combined with the electrical properties of dust, would help to constrain the magnitude of these risks. Electricity investigations should specifically determine if higher frequency (AC) electric fields are present between the surface and the ionosphere, over a dynamic range of 10 µV/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. 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 free of biohazards is not the same as proving that life does not exist anywhere on Mars.*

<u>Investigation B2.1:</u> 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. (High Priority)

This Investigation 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 other 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 as it would not be possible to prevent human contact with the dust. Thus, 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. For both determining the presence of extant life and assessing if dust is the mechanism for its transport, 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. One of the major mission objectives of the proposed human mission would be to determine if and how life arose naturally on Mars.

<u>Investigation B3.1:</u> Map the distribution of both naturally occurring Special Regions, and regions with the potential for spacecraft-induced Special Regions, as defined by COSPAR5 (High Priority).

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. This Investigation focuses on acquiring data needed to evaluate the extent of this potential compromise.

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: Understand the resilience of atmospheric In Situ Resource Utilization (ISRU) processing systems to variations in Martian near-surface environmental conditions (High Priority).**

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.

<u>Investigation B4.1:</u> Test ISRU atmospheric processing system to measure resilience with respect to dust and other environmental challenge performance parameters that are critical to the design of a full-scale system (High Priority).

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) equipment 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 Mars Oxygen ISRU Experiment (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. Although MOXIE is anticipated to sufficiently address this Investigation, success will not be assumed until that mission is complete.

**Sub-objective B5: Assess landing site-related hazards, including those related to safe landing and safe operations (including trafficability) within the possible area to be accessed by elements of a human mission (Medium Priority).**

Humans landing and working on the surface of Mars will interact 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.

Investigation B5.1: Image selected potential landing sites to sufficient resolution to detect and characterize hazards to both landing and trafficability at the scale of the relevant landed systems (High Priority).

Investigation B5.2: Determine regolith physical properties and structure (including particle shape and size distribution), gas permeability of the regolith and the chemistry and mineralogy of the regolith, including ice contents (Medium Priority).

For Investigations B5.1 and B5.2, 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.

Specific measurements regarding regolith physical properties and structure includes presence of significant heterogeneities or subsurface features of layering, with measurements of 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/cm$^3$, as well as an index of shear strength. Gas permeability of the regolith should be measured in the range 1 to 300 Darcy with a factor of three for accuracy. Measurements are needed for regolith particle shape and size distribution, as well as Flow Rate Index test or other standard flow index measurement on the regolith materials. Finally, measurements are needed to determine the chemistry and mineralogy of the regolith, including ice contents.

*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 the Mars Exploration Rovers (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.

*To date, we have some knowledge about:*

1) 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, MER *Spirit*, and MSL Curiosity (hummocky plains). We also know a bit about what makes the soils cohesive, where they are dominated by sulfate-rich salts.
2) 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) 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.

**Sub-objective B6: 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. In addition to biohazards (Sub-objective B2), the primary gaps in our knowledge about potential harmful environmental effects include the radiation environment and dust toxicity of surface regolith.

Investigation B6.1: Measurement of neutrons with directionality. Energy range from <10 keV to >100 MeV (Medium Priority).

Investigation B6.2: Measure the charged particle spectra, neutral particle spectra, and absorbed dose at the Martian surface throughout the ~11 year solar cycle (from solar maximum to solar minimum) to characterize "extreme conditions" (particle spectra from solar maximum and minimum, as well as representative "extreme" solar energetic particle (SEP) events), and from one solar cycle to the next (Medium Priority).

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 an adequate global, intrinsic magnetic field, thus posing a higher risk to radiation exposure. As energetic particles dissipate energy into the Martian atmosphere and regolith due to the background galactic cosmic rays (GCRs) and solar energetic particles (SEPs), they produce a host of secondary particles, especially after 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 (currently in its third Earth year). 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 are unlikely to be fully characterized by MSL due to solar variability (few or no significant CMEs during the mission).

Investigation B6.3: Assay for chemicals with known toxic effect on humans, particularly oxidizing species (e.g., Cr(VI)), in samples containing dust-sized particles that could be ingested. Of particular interest is a returned sample of surface regolith that contains airfall dust, and a returned sample of regolith from as great a depth as might be affected by surface operations associated with human activity (EVA, driving, mining, etc.) (Low Priority).

Investigation B6.4: Fully characterize soluble ion concentrations, and chemical reactions that occur upon humidification, using the same kinds of samples described in Investigation B6.5 (Low Priority).

Investigation B6.5: Analyze the shapes of Martian dust grains with a grain size distribution (1-500 microns) sufficient to assess their possible impact on human soft tissue (especially eyes and lungs) (Low Priority).

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”, which is 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. Also discussed in the report are 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. 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 EVA systems, as well as dust mitigation protocols and design features, would already be significant, driven by other environmental challenges and forward and back contamination protocols.

**Sub-objective B7: 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 (Low Priority).**

Mars is a dry, dusty place. We need to understand the potential impacts of dust on a crewed mission to the Martian surface. Within this Sub-objective, we focus on the effect of dust on the engineering system that would keep the humans on Mars alive and productive (versus the direct effects of Martian dust on human beings, which are included in Sub-objective B6, or the effect of dust on ISRU systems which is within Sub-objective B4).

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.

Past experience with lunar surface astronaut operations as part of the Apollo program illuminated 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, which are capable of raising and transporting dust.

This Sub-objective requires collecting enough data about the Martian dust to also 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.

<u>Investigation B7.1:</u> 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 (Low Priority).

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. Although partial information exists on grain shape and size distribution, density, shear strength, ice content and composition, and mineralogy, especially from Gale Crater, these data should be extended to at least one other site with different geologic terrain. Furthermore, there is still a dearth of data regarding the electric and thermal conductivity, triboelectric and photoemission properties and associated chemistry of the fines.

<u>Investigation B7.2:</u> Determine the electrical conductivity of the ground, measure the magnitude and dynamics of any quasi-DC electric fields, and determine the charge on individual dust grains (Low Priority).

Specific measurements needed include determination of any quasi-DC electric fields with a dynamic range of 5 V/m-80 kV/m, with a resolution $\Delta V = 1V$, over a bandwidth of DC-10 Hz (measurement rate = 20 Hz) as well as determination of 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.

Investigation B7.3: Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the Martian atmosphere (Low Priority).

## 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.

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, along with 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 its moons (see Goal III, Objective C). 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 so incomplete that we do not have enough information 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 required/desired commodities. Detailed understanding of the presently unkown surface composition will drive science and exploration objectives and may also influence systems design.

Investigation C1.1: Determine the elemental and mineralogical composition of the surface and near sub-surface of Phobos and Deimos (High Priority).

Investigation C1.2: Identify geologic units for science and exploration and materials for future in situ resource utilization operations (High Priority).

Investigation C1.3: Determine the gravitational field to a sufficiently high degree and order to make inferences regarding the internal structure and mass concentrations of Phobos and Deimos (Medium Priority).

**Sub-objective C2: Understand the conditions at the surface and the low orbital environment for the Martian satellites sufficiently well so as 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, so as to design the engineered systems. In addition to the orbital particulate population (Sub-objective A2), this includes 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, as well as detailed characterization of the thermal conditions as they relate to the vehicle, EVA and tool design.

<u>Investigation C2.1:</u> Measure and characterize the physical properties and structure of regolith on Phobos and Deimos (High Priority).

<u>Investigation C2.2:</u> Determine the gravitational field to a sufficiently high degree to be able to carry out proximity orbital operations (Medium Priority).

<u>Investigation C2.3:</u> Measure the electrostatic charge and plasma fields near the surface of Phobos and Deimos (Low Priority).

<u>Investigation C2.4:</u> Measure the surface and subsurface temperature regime of Phobos and Deimos to constrain the range of thermal environments of these moons (Low Priority).

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

*To achieve Objective D, the Investigations in Objectives A and B should be completed, along with the following:*

**Sub-objective D1: Characterize potentially extractable water resources to support 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 (see DRA 5.0/Drake 2009). For the purpose of this planning, it is assumed that information about ISRU related to extraction of resources from the atmosphere is needed as part of Objective B (Sub-objective B4), 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 falls into 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. These deposits are attractive candidates for ISRU because: 1) they exist on the surface, thus their surface spatial distributions can be constrained (in dust-free areas) using remote methods, 2) they exist in a variety of locations across the globe, thus providing 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 at most high-latitude sites is likely to be in the form of subsurface ice. In addition, theoretical models can predict subsurface ice in some mid-latitude regions, particularly on poleward facing slopes. Indeed, ice at northern latitudes as low as 42° has been detected in fresh craters using high-resolution imaging and spectroscopy. Based on observed sublimation rates and the color of these deposits, the ice is thought to be nearly pure with <1% debris concentration. Pure subsurface ice and other ice-cemented soil were also detected by the Phoenix mission. 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 excavatability, 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.

Investigation D1.1: Identify a set of candidate water resource deposits that have the potential to be relevant for future human exploration (High Priority).

In identifying candidate water resource deposits, enough information needs to be collected to be able to identify, characterize (from reconnaissance data), and prioritize the targets identified and to guide engineering/technology planning and architectural decisions related to water-based ISRU.

Investigation D1.2: Prepare high spatial resolution maps of at least one high-priority water resource deposit that include the information needed to design and operate an extraction and processing system with adequate cost, risk, and performance (High Priority).

To prepare high spatial resolution maps, information needs include but may not be limited to: depth-concentration relationship of the water-bearing phase(s), map-view spatial relationships, and physical properties of the water-bearing material.

Investigation D1.3: Measure the energy required to excavate/drill and extract water the H-bearing material from either shallow water ice or hydrated minerals as appropriate for the resource (Medium Priority).

# Integrating the Goals to Understand Mars and Beyond

The Goals, Objectives, Sub-objectives, and Investigations discussed in the previous sections are elements of the overall effort to understand:

1) Mars as a system, in all of its complexity,
2) the long-term evolution of habitability on Mars within that complex system,
3) what Mars has to tell us about the Earth and the other planets of our Solar System (and potentially even beyond our Solar System), and
4) what is needed to prepare for humankind's first steps on another planet.

The first three of these elements are traceable to the *Vision & Voyages'* cross-cutting science themes of building new worlds, planetary habitats, and solar system workings (NRC, 2011), but in many ways they provide a more balanced perspective for what may emerge from the study of Mars. The material presented in the Goals chapters of this document — like Mars itself — does not fit neatly even into these integrating categories or the evolving Mars Exploration Program themes, as there are many cross-cutting relationships between them. They serve, however, to illustrate how Goals I-IV and their many components, considered together, lead to a greater understanding of Mars.

## Understand Mars as a System

Orbital, landed, laboratory (including meteorite studies and other kinds of experiments), and modeling studies over the last ~15 years have shown that Mars is significantly more diverse and complex than had been previously thought. Truly understanding the implications of individual Objectives and Investigations for Martian life, climate, and geology requires understanding their interactions and interdependencies as a system through Martian history. For example:

- Within Goals II and III, numerous high-level Mars science questions relevant for interpretation of the history of Mars involve interactions between the atmosphere, the surface, and subsurface. For example, what were the environmental conditions on ancient Mars, how did they come into being, when and why did they change, and what evidence of their existence and evolution is preserved? More recently, how does the volatile reservoir within the polar caps (and thus the atmosphere) change through obliquity cycles?
- Goal I also may feed into these questions as lifeforms are affected by, but also alter, the environments produced by climate and geological processes.

## Understand the Long-Term Evolution of Habitability on Mars

The habitability of Mars increasingly is understood as a feature that emerges from and changes with the interaction of geological processes, climate and atmospheric evolution, and stellar evolution. Mars is the most readily accessed planetary body (other than 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 or elsewhere in our Solar System, 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, involving Investigations from Goals I, II, and III:

- In Goal I, the principal aim of characterizing habitability is to inform the selection of sites, or of samples from those 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 provide key insights with respect to characterizing the evolution of habitability, including: characterizing the evolution of the Martian hydrological cycle, emphasizing likely changes in the location and chemistry of liquid water reservoirs; constraining 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); constraining 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; evaluating the changing nature and magnitude of oxidative or radiation hazards at the surface and in the shallow crust.

## Inform Comparative Planetology

The study of the Earth would be a compelling endeavor even if there were no other planets in the Solar System. However, the fact that there are other planets and that we have space-age observations of them provides provocative new insights into our study of Earth. Mars historically has played a special role in this endeavor and continues to do so. For example:

- As a well-studied, accessible planetary body with a variety of information available over a vast range of spatial and temporal scales, Mars provides vital information about geologic processes relevant to rocky planet evolution and development, and the evolution of habitability in our Solar System.
- Studies of atmospheric and surface processes under Martian conditions can be compared and contrasted with similar studies under terrestrial or other conditions; such comparisons enable a better understanding of these processes as a whole. The comparison with Earth is especially strong here in that both Earth and Mars are rapidly rotating planets with relatively shallow atmospheres heated largely from the surface.

Such comparative studies provide a compelling, larger-than-Mars framework for all four Goals.

Although many people think primarily about Mars in relation to similarities and differences from Earth, there are also comparisons to be considered with Venus (e.g., types of volcanism and how lava type and flow are influenced by planetary conditions; interactions with the solar wind), Titan (e.g., sand dune migration and evolution), the Moon (e.g., impactor flux variation through the Solar System), Europa (e.g., cause and impact of plate tectonics), and/or exoplanets (e.g., habitability). Comparisons can be made on even grander scales, with overarching science questions including “How does life start?”, “How can climate change occur over geologic time and how extreme can it be?”, and “How do planetary interiors evolve?” Thus, an integrated understanding of how planetary processes compare with one another informs and is informed by a growing set of observations of potentially habitable worlds both within and beyond our Solar System.

**Exploration by Humans on Mars**

To design missions for sending humans to Mars' surface with acceptable risk and cost, we need to know the ways in, and degree to, which Mars is similar (or not) to the environments within which humans generally live. The information needed to understand Mars as a system, the degree to which it is or was habitable and possibly even inhabited, and why it and the other planets are what they are is commonly the same information needed to establish the resources that Mars can provide for in situ exploration by humans and to scope how to make further progress in understanding our planetary neighborhood and beyond.

# Appendices

## App. 1: References (to full document, including App 3 and 4)

Baross, J.A. (2007) The limits of organic life in planetary systems, National Academies Press, Washington, D.C., 100 p.

Beaty, D.W., Snook, K., Allen, C.C., Eppler, D., Farrell, W.M., Heldmann, J., Metzger, P., Peach, L., Wagner, S.A., and Zeitlin, C., (2005). An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

Drake, B.G, editor, (2009). NASA/SP-209-566, Mars Design Reference Architecture 5.0, 83p document posted July, 2009 by the Mars Architecture Steering Group at http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf

Hinners, N.W., Braun, R.D., Joosten, K.B., Kohlhase, C.E., and Powell, R.W., (2005), Report of the MEPAG Mars Human Precursor Science Steering Group Technology Demonstration and Infrastructure Emplacement (TI) Sub-Group, 24 p. document posted July, 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

*(All MEPAG Goals Documents can be downloaded from http://mepag.nasa.gov/reports.cfm.)*

MEPAG (2001), Scientific Goals, Objectives, Investigations, and Priorities, in Science Planning for Exploring Mars, JPL Publication 01-7, p. 9-38.

MEPAG (2004), Scientific Goals, Objectives, Investigations, and Priorities: 2004, G. J. Taylor, ed., 23 p. white paper posted July, 2004.

MEPAG (2005), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2005, 31 p. white paper posted August, 2005.

MEPAG (2006), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2006, 31 p. white paper.

MEPAG (2008), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2008, J.R. Johnson, ed., 37 p. white paper posted September, 2008.

MEPAG (2010), Mars Scientific Goals, Objectives, Investigations, and Priorities: J.R. Johnson, ed., 49 p. white paper posted September, 2010.

MEPAG (2014), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2012 V. Hamilton, ed., 52 p. white paper posted September, 2014.

MEPAG (2015), Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015. V. Hamilton, ed., 74 p. white paper posted June, 2015.

NRC (2002), Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface, Chair: Hauck, *National Academies Press, Washington, D.C.*, ISBN: 978-0-309-08654-7.

NRC (2007), An Astrobiology Strategy for the Exploration of Mars, Chair: Jakosky, *National Academies Press, Washington, D.C.,* ISBN: 978-0-309-10851-5.

NRC (2013), Vision and Voyages for Planetary Science in the Decade 2013-2022, Steering Group Chair: Squyres, *National Academies Press, Washington, D.C.*, ISBN: 0-309-20955-2.

Piqueux, S., Byrne, S., Kieffer, H.H., Titus, T.N., and Hansen, C.J. (2015), Enumeration of Mars years and seasons since the beginning of telescopic exploration, *Icarus* 251, 332-338, doi:10.1016/j.icarus.2014.12.014.

P-SAG (2012) Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System: Final report of the Precursor Strategy Analysis Group (P-SAG), D.W. Beaty and M.H. Carr (co-chairs) + 25 co-authors, sponsored by MEPAG/SBAG, 72 pp., posted July 2012, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

Rummel, J.D., Race, M.S., DeVincenzi, D.L., Schad, P.J., Stabekis, P.D., Viso, M., and Acevedo, S.E., editors. (2002) A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth [NASA=CP-20-02-211842], NASA Ames Research Center, Moffett Field, CA.

# App. 2: Acronyms used

| | |
|---|---|
| **CME** | Coronal Mass Ejections |
| **DRA** | Design Reference Architecture |
| **EDL** | Entry, Descent, Landing |
| **EMC** | Evolvable Mars Campaign |
| **EPS** | Extracellular Polymeric Substances |
| **ESA** | European Space Agency |
| **EUV** | Extreme UV |
| **GCR** | Galactic Cosmic Rays |
| **InSight** | Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (mission) |
| **IR** | Infrared |
| **ISRU** | In situ resource utilization |
| **LET** | Linear Energy Transfer |
| **MAVEN** | Mars Atmospheric and Volatile Evolution (mission) |
| **MECA** | Microscopy, Electrochemistry, and Conductivity Analyzer (instrument, Phoenix) |
| **MEDLI** | Mars Science Laboratory Entry Descent and Landing Instrument (instrument, MSL) |
| **MEP** | Mars Exploration Program |
| **MEPAG** | Mars Exploration Program Analysis Group |
| **MER** | Mars Exploration Rover (mission): *Spirit* and *Opportunity* (rovers) |
| **MEx** | Mars Express (mission) |
| **MGS** | Mars Global Surveyor (mission) |
| **MRO** | Mars Reconnaissance Orbiter (mission) |
| **MSL** | Mars Science Laboratory (mission): Curiosity (rover) |
| **MTAO** | Mars Take-off, Ascent and Orbit-insertion |
| **MY** | Mars Year, a date-convention for Mars observations (see Piqueux et al. 2015) |
| **NIR** | Near-IR |
| **NRC** | National Research Council |
| **PBL** | Planetary Boundary Layer |
| **PLD** | Polar Layered Deposits |
| **P-SAG** | Precursor Strategy Analysis Group (report: Analysis of Strategic Knowledge Gaps Associated with Potential Human Missions to the Martian System) |
| **RAD** | Radiation Assessment Detector (instrument, MSL) |
| **RSL** | Recurring Slope Lineae |
| **SEP** | Solar Energetic Particle |
| **SBAG** | Small Bodies Assessment Group |
| **SKG** | Strategic Knowledge Gap |
| **SRP** | Supersonic Retro-Propulsion |
| **TEGA** | Thermal and Evolved Gas Analyzer (instrument, Phoenix) |
| **TGO** | Trace Gas Orbiter (mission) |
| **UV** | Ultraviolet |

# 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 (Baross 2007):

- Life 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.
- Life probably requires a liquid solvent to support such molecular interactions.
- Life 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. Although 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, although 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 prebiotic 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"/Baross 2007) 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 A1 and B1 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. Although 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.

Although 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 commonly 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.

<u>3) Physical structures:</u> 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 that mimic biological morphologies. When both abiotic and biotic morphologies are known to exist, neither can be used to support a definitive interpretation of a feature. Rather the interpretation of the feature will remain ambiguous in the absence of additional discriminating observations.

<u>The problem of contamination:</u> Any of the classes of biosignature evidence that might be sought to address Sub-objectives A3 and B3 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. Further, spacecraft components, although not contaminants themselves if intended for flight, could compromise biosignature dections in the same manner as contaminants, if those components suffer damage or wear. For example, physical wear can lead to the shedding of particulates and broken seals can lead to the redistribution of chemicals. Spacecraft hardware design and operations must consider risk mitigation steps to control the use and distribution of internal calibrants, reagents, and materials of the spacecraft after minor damage or wear during the mission so that background noise in experiments are maintained at levels that do not unintentionally compromise signal detections of biosignatures of all classes. 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. Commonly, 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, whereas 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.

<u>Preservation of physical structures:</u> 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.

<u>Preservation of biominerals:</u> 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/Drake 2009). 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, including those relevant to human missions to Phobos/Deimos[10].

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 (2010) 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 into Objective A (leaving only Objective A). There was previously an unnecessarily high degree of overlap between the two.

The previous (to 2010) 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 and Hinners et al. 2005). Each prepared reports that became the foundations for, in those revisions, 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. 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 being retired in this Version

Four 2012 MEPAG Investigations are retired in this (2015) MEPAG Goals document, as measurements since 2010 have sufficiently contributed towards completion.

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[10] See the MEPAG (http://mepag.nasa.gov/reports.cfm?expand=topical ) or SBAG (http://www.lpi.usra.edu/sbag/) websites for details about P-SAG, and the final report.

| P-SAG SKGs | 2012 MEPAG Sub-objective | 2012 MEPAG Investigation |
|---|---|---|
| B6-3. Trace gas abundances | B5 – Atmospheric ISRU | Measure the trace gas composition of the Martian atmosphere with sufficient resolution and accuracy to detemine the potential effects on atmospheric ISRU. |
| B7-3. Trafficability | B6 – Landing Site and Hazards | Determine traction/cohesion in Martian regolith throughout planned landing sites; where possible, feed findings into surface asset design requirements. 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/cm$^3$. |
| B3-2. Simultaneous spectra of solar energetic particles in space and in the surface | B7 – Crew Health and Performance | Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in solar energetic particle events. |
| B3-4. Spectra of galactic cosmic rays on surface | B7 – Crew Health and Performance | 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 determine the potential effects on atmospheric ISRU.* Measurement of trace gases in the Martian atmosphere by MSL has provided sufficient information about the well-mixed Martian atmosphere 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. 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.* From investigations by the Viking and Phoenix landers, and the rovers Pathfinder, MER *Spirit*, MER *Opportunity*, and MSL *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 satelites 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.

## Mapping of Investigations to Mars Strategic Knowledge Gaps (SKGs)

***Table App. 4-1****: Partial listing of P-SAG Strategic Knowledge Gaps (SKGs) and Gap-filling Activities (GFAs). This table focuses on the GFAs to be performed at Mars; See the full P-SAG report and associated matrix for details, including technology demonstrations and investigations not needing Mars flight opportunities.*

| **P-SAG** | | **2015 MEPAG Goals** | | |
|---|---|---|---|---|
| **SKG** | **GFA** | **Sub-obj.** | **Inv.** | **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 | Medium |
| A3. Orbital Particulates | A3-1. Orbital particulate environment | A2 | A2.1 | Medium |
| B1. Lower Atmosphere | A1-2. Global aerosol profiles and properties, B1-1. Dust Climatology | B1 | B1.1 | High |
| | B1-2. Global surface pressure; local weather | | B1.2 | High |
| | A1-1. Global temperature field | | B1.3 | High |
| | B1-3. Surface winds | | B1.4 | Medium |
| | B1-4. EDL profiles | | B1.5 | Medium |
| | B1-5. Atmospheric electricity conditions | | B1.6 | 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 |
| B6. Atmospheric ISRU | (Atmospheric ISRU processing) **NEW** | B4 | B4.1 | High |
| B7. Landing Site and Hazards | B7-2. Landing site selection | B5 | B5.1 | High |
| | B7-1. Regolith physical properties/structure | | B5.2 | Medium |
| B3. Crew Health & Performance | B3-1. Neutrons with directionality | B6 | B6.1 | Medium |
| | (Spectra of solar energetic particles on the surface) **NEW** | | B6.2 | Medium |
| | B3-5. Toxicity of dust to crew | | B6.3 | Low |
| | | | B6.4 | Low |
| | | | B6.5 | Low |
| B4. Dust Effects on Surface Systems | B4-2. Dust physical, chemical and electrical properties | B7 | B7.1 | Low |
| | B4-1. Electricity | | B7.2 | Low |
| | B6-2. Dust column abundances | | B7.3 | Low |
| C1. Phobos/Deimos (P/D) Surface Science | C1-1. Surface composition | C1 | C1.1 | High |
| | | | C1.2 | High |
| | C2-2. P/D Gravitational field | | C1.3 | Medium |
| C2. Phobos/Deimos Surface Operations | C2-3. P/D regolith properties | C2 | C2.1 | High |
| | C2-2. P/D Gravitational field | | C2.2 | Medium |
| | C2-1. P/D Electric and plasma environments | | C2.3 | Low |
| | C2-4. P/D thermal environment | | C2.4 | Low |
| D1. Water Resources | (Mapping of water resources) **NEW** | D1 | D1.1 | High |
| | D1-4. Hydrated mineral occurrences & D1-6. Shallow water ice occurrences | | D1.2 | High |
| | D1-5. Shallow water ice composition and properties | | D1.3 | Medium |