Mars Science Goals, Objectives, Investigations, and Priorities: 2020 Version [DRAFT]

Mars Exploration Program Analysis Group (MEPAG)

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PREAMBLE

NASA's Mars Exploration Program (MEP) has requested that the Mars Exploration Program Analysis Group (MEPAG) maintain the MEPAG Mars Science Goals, Objectives, Investigations, and Priorities document (colloquially—and hereinafter, 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 and in support of 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 years[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 NASA as well as other space agencies around the world that provide funding for flight missions. A separate, unrelated process for forward planning—similar in some ways to the Goals Document—is the Planetary Science Decadal Survey, which is prepared once every ten years by the National Academies of Sciences, Engineering, and Medicine (NASEM) (e.g., Vision and Voyages for Planetary Science in the Decade 2013-2022 (NRC, 2013)). The MEPAG Goals Document constitutes one of many inputs into the Decadal Survey discussion, even though these two organizations operate independently.

This version of the MEPAG Goals Document is again organized into a four-tiered hierarchy: Goals, Objectives, Sub-Objectives, and Investigations. The Goals are organized around four major areas of scientific knowledge, commonly referred to as Life (Goal I), Climate (Goal II), Geology (Goal III), and Preparation for Human Exploration (Goal IV); expanded statements of the Goals are found in the respective chapters. 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 because 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-Objectives include more detail and clarity on different parts of Objectives, but cover tasks that are larger in scope than Investigations.

The Investigations that go into collectively achieving 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 an investigations are discussed; however, how those measurements should be made is not specified by this Goals Document, allowing the competitive proposal process to identify the most effective means (instruments and/or missions) of making progress towards their realization.

It should be noted that completion of all of the investigations in the MEPAG Goals Document would require decades. Given the complexity involved, it is also possible that they might never be truly complete: observations answering old questions often raise new questions. Thus, evaluations of prospective instruments and missions should be based on how well Investigations are addressed

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[1] All MEPAG Goals Documents are listed at the end of the Preamble and can be found at https://mepag.jpl.nasa.gov/reports.cfm?expand=science.

and how much progress might be achieved in the context of that specific instrument or mission.

Finally, this updated hierarchy has been augmented with a spreadsheet that shows the traceability from each Goal to its Investigation tier, enabling readers to view the entirety of each Goal "at a glance". The introduction to each Goal chapter includes a portion of this spreadsheet outlining the Objectives and Sub-Objectives for that Goal. The full spreadsheet—including all Goals, Objectives, Sub-Objectives, and Investigations—accompanies this Goals 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 in achieving a stated objective
- Identification of logical sequential relationships
- Cost, risk, and feasibility of implementation

If additional criteria have been applied within an individual goal, they are described in the relevant chapter. The specific labels used within a Goal to demark priority are also described at the beginning of the relevant goal chapter.

Although priorities should influence which investigations are conducted first, the order of investigations as presented within a goal is not meant to imply that they need to be undertaken in sequence, except where it is noted that a specific Investigation should be completed first. In such cases, the Investigation that should be undertaken first (as a prerequisite) is given a higher priority, even when it is believed that a subsequent Investigation ultimately would be more important, and the suggested order is specified.

Integrating the MEPAG Goals to Understand Mars and Beyond

Most of Mars science is, by nature, cross-cutting. For example, geological and mineralogical evidence for long-lived standing bodies of water in the ancient past provides a constraint for climate models. Because such interrelationships are difficult to appreciate within the hierarchical structure of this Goals document, yet they are what make Mars investigations so compelling within the broader scope of solar system science, we have included a final chapter—entitled "Integrating the MEPAG Goals to Understand Mars and Beyond"—to identify and explain the important scientific pursuits that extend across the boundaries of our four Goals. We have organized this chapter using the overarching questions (or "Big Questions") in Planetary Science that the MEPAG community developed in response to a request of the NASA Planetary Science Division Director in 2019. Discussing how our Goals map onto these overarching questions, which span all of planetary science, underscores how the Mars Program contributes to our understanding of our solar system and planetary systems in general.

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

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

https://mepag.jpl.nasa.gov/reports.cfm?expand=science

Investigations are recognized in the text of each Goal chapter. The identification of specific interrelationships at the Investigation level is intended to help members of the scientific and engineering communities determine the broader impacts of research and/or development activities undertaken in association with the flight program. The list of cross-cutting Investigations is meant to be thorough but is not expected to be complete.

Additional Notes Relating to the 2020 Version of the Goals Document

This document is a complete revision of the MEPAG Goals Document in that all areas covered by the document were reviewed for updating (further details on changes made are below); the preceding complete revision of the document was done in 2015. A 2018 revision updated Goals II and III in response to discoveries and analyses showing a disconnect between high-priority science questions regarding polar and non-polar ice questions as compared with the 2015 version of the MEPAG Goals Document. Because this latest (2020) revision examined all aspects of the Goals Document, the Goal representatives considered content at all levels, prioritization, and structure. While some parts remained as they were, several Investigations were added, removed, or changed in response to the advances that have been made in understanding Mars; furthermore, the division of Sub-Objectives was changed in some places to better reflect the main directions of inquiry at the present time (in particular, within Goals III and IV). Similarly, priorities were adjusted throughout the document to reflect progress in our understanding of Mars, as well as the evolving plans for humans to explore Mars, since 2015.

The Goals Committee would like to extend its appreciation to the leaders of the Integration teams who summarized the state of Mars science at The Ninth International Conference on Mars and who contributed to the discussions of the Goals Committee: Dave Des Marais (Life), Francois Forget (Climate), and Wendy Calvin (Geology). Paul Niles, who led the Integration team for Preparation for Human Exploration, is also an author of this Goals document.

Section of the Goals Document	**Date of Update**	**Date of Previous Significant Update**
Goal I: Determine If Mars Ever Supported Life	**2020 (this document)**	2015
Goal II: Understanding the Processes and History of Climate on Mars		2018
Goal III: Understand the Origin and Evolution of Mars as a Geological System		2018
Goal IV: Prepare for Human Exploration		2015
Integrating Across the MEPAG Goals to Understand Mars and Beyond		2015

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.

2018 version: Don Banfield, Sarah Stewart Johnson, Jennifer Stern, David Brain, Paul Withers, Robin Wordsworth, Steve Ruff, R. Aileen Yingst, Jacob Bleacher, Ryan Whitley

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

Change since the 2018 version of this document

We have compiled here a discussion of the changes in each Goal Chapter from the previous (2018) version of this document (which in some cases was the same as the 2015 version). For new readers of this document, this section is only of historic significance, and it is likely more useful to go directly to the Goal chapters. For readers familiar with previous versions of this document, this section highlights where changes have occurred in this revision, however the discussion assumes that the reader is already familiar with each Goal chapter.

Goal I: Determine if Mars ever supported life

Distinguishing between "past" and "extant" life

Previous versions of Goal I distinguished between "past" and "extant" life. The present version of Goal I does not make that distinction, for the following reasons:

- Searching for evidence of past life or of extant life are two different mission implementation strategies, neither of which is intrinsically more meritorious than the other. Both strategies have advantages and disadvantages that cannot be fully addressed in this document. For example, a search for evidence of metabolically viable organisms could target multiple classes of biosignatures, including chemical, structural and physiological ones[3]. Such biosignatures – if present – ought to be relatively well-preserved. However, in order to succeed, such a strategy must make a compelling case for habitability in an environment that is generally assumed to be too extreme to sustain life, at least near the surface. On the other hand, a search for evidence of past life can be justified on the grounds that habitable conditions have already been

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[3] Details on all three classes are provided in the Goal I main text below (see Goal I, Objective A).

established for environments that existed early in the history of the planet. However, biosignatures of a past biosphere must have survived billions of years of chemical and physical diagenesis in order to be detectable today. The merits and demerits of each mission implementation strategy are better assessed in other forums that evaluate specific mission concepts, such as the Planetary Sciences Decadal Survey, Science Definition Team Reports or mission program review panels. This assessment approach is deemed more productive compared to separating both mission implementation strategies and prioritizing one over the other in this document.

- While assessing the metabolic state of putative forms of life on Mars would be of high scientific interest, this is considered of secondary importance compared to assessing the presence or absence of life, in the present or past. Instead of a binary choice between searching for biosignatures of past life or of extant life, biosignatures can be considered as a continuum which includes alive, dead, and degraded, none of which has a higher priority than the other in the context of addressing Goal I. Further investigations into the metabolic state of martian life would undoubtedly follow a positive detection of biosignatures.
- Some of the more conclusive strategies, technologies and biosignatures used to search for evidence of life cannot discriminate between extant and past forms of life. For example, evidence of life might be obtained using mass spectrometry in the form of unusual distribution abundances of organic compounds, such as lipids or amino acids, or in their carbon isotopic ratios. Such results (when coupled with other requisite contextual measurements) could be interpreted as conclusive evidence of life, whether extant or extinct. Assessing the metabolic state of life would require additional measurements not needed to address Goal I.
- Some environments on Mars could have a high potential for both past and recent habitability. For example, Noachian/Hesperian evaporitic deposits could contain evidence of an early martian biosphere, but they could also have created habitable conditions much later in the history of the planet, perhaps up to recent times, as is observed in some of the driest regions on Earth. Similarly, ice-bearing permafrost, which on Mars could be significantly older than on Earth, could preserve evidence of past life, but could also have created a transient habitable environment during warmer periods triggered by recent orbital fluctuations. In such instances, mission concepts to search for evidence of life could target biosignatures of extant AND of past life, without the need for prioritization.

Assessing abiotic organic chemical evolution

The 2001 version of Goal 1 included the third objective “Assess the extent of prebiotic organic chemical evolution” that was subsequently eliminated in newer versions. Several recent discoveries warrant that assessments of organic chemical evolution be merged back into Goal 1:

- The discovery of past habitable environments does not imply that life ever existed on Mars. However, organic chemical evolution would still have occurred even on a lifeless planet. Mars could be a unique scientific opportunity to better understand the sequence of prebiotic steps that led to the origin of life on Earth.
- The recent detection of organic matter in sedimentary deposits at Gale Crater demonstrates that organic molecules can accumulate and be preserved near the surface, arguably with diagenetic alterations, for geologic periods of time. Objective A considers the possibility that those organic molecules, and other organic compounds that might be discovered at different landing sites, were generated by biology. Objective B balances that equation by considering

alternative abiotic explanations. Ultimately, both objectives represent contrasting hypotheses that complement and reinforce each other.

- The detection of reduced and oxidized forms of carbon (e.g., CO_2, CH_4, carbonates, organics), nitrogen (e.g., N_2, nitrates) and sulfur (e.g., sulfides, sulfates, sulfur-bearing organics) suggests that synthesis of prebiotically relevant organic compounds could have been common on Mars in the past, or could be presently occurring. Internal mechanisms of abiotic organic synthesis could complement exogenous sources (e.g., carbonaceous meteorites).

Goal II: Understand the processes and history of climate on Mars

In general, Goal II was edited for clarity and the overall length was shortened to facilitate use of the document and increase its accessibility and impact. In particular, in Objective A, the text was reduced to bring the discussion more in line with the other Objectives and indeed the other Goals. Additionally, in Objective A, the Sub-Objectives were re-organized and clarified. Prioritizations were updated in light of new results from recent missions (particularly MAVEN). Objective B also had a re-ordering and re-prioritization of its Sub-Objectives, again based on recent advances. Objective C had one Sub-Objective removed and the other two were restructured. More detail was added on the investigations needed for constraining atmospheric evolution.

Goal III: Understand the origin and evolution of Mars as a geological system

Relative to the 2018 version, the largest modifications in Goal III have been made within Objective A. (Only minor updates were incorporated into Objectives B and C.) Objective A is restructured to focus on specific, actionable strategic knowledge gaps. Investigations in this Objective are grouped into sub-objectives around themes of past and present water reservoirs, sediments & sedimentary deposits, environmental transitions, and the planet's geologic history. No Goal III, Objective A investigations from the prior (2018) version were removed, although many are captured across multiple investigations in this version (see Appendix 4). Two new investigations were added to address the history of sulfur and carbon (Investigation A3.4) and to link martian meteorites and returned samples to Mars' geologic evolution (A4.3).

Goal IV: Prepare for human exploration

The anticipated beginning of the Artemis program and the Moon to Mars effort has inspired a broad reclassification at the objective level. Instead of focusing objectives around a particular architecture, objectives have been recast to cover broad topics such as landing, surface exploration, ISRU, planetary protection, and exploration of the martian moons. As of early 2020, many details of the human Mars exploration architecture remain unclear and the new organization adopted here should provide a more flexible format. In particular architectures may or may not include particular elements like ISRU or investigations of special regions. To that end, no prioritization at the Objective level is proposed at the present time.

In detail, Objectives A, B, and D from the previous (2015 and 2018) Goals Document were divided into Objectives A, B, C, and D in this new revision. Objective C regarding Phobos and Deimos remained largely untouched and was moved to Objective E in the new revision. All of the sub-objectives from 2015/2018 were either kept largely intact or modified to accommodate the new objective structure. There were also two new Sub-Objectives added for the new revision: B3 which dicusses dust storms specifically, and D4 which is focused on preparing for careful monitoring of changes created by human presence.

GOAL I: DETERMINE IF MARS EVER SUPPORTED LIFE

Objectives	Sub-Objectives
A. Search for evidence of life in environments that have a high potential for habitability and expression/preservation of biosignatures.	A1. Determine if signatures of life are present.
	A2. Investigate the nature and duration of habitability.
	A3. Assess the preservation potential of biosignatures.
B. Assess the extent of abiotic organic chemical evolution.	B1. Constrain atmospheric and crustal inventories of carbon (particularly organic molecules) and other biologically important elements over time.
	B2. Constrain the surface, atmosphere, and subsurface processes through which organic molecules could have formed and evolved over martian history.

The search for evidence of life beyond Earth remains one of the highest goals in planetary exploration, and Mars is a high priority destination in this quest. 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 that life could also have evolved on Mars. The documented history of past habitable conditions on Mars and the discovery of organic matter in sedimentary deposits suggest that signatures of life could be detectable. Current and emerging technologies enable us to evaluate this possibility with scientific rigor.

Previous versions of Goal I distinguished between "past" and "extant" life. "Extant" life refers to life that is metabolically active or that could become metabolically active under favorable conditions, whereas "past" life refers to any life that does not meet this criterion. The present version of Goal I does not make that distinction, for reasons outlined in the Preamble and in Appendix 3. The implications of a positive detection for either extinct or extant life 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 biochemistry, structure 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. Discovery of an extant biosphere would also impact the future exploration of Mars with humans (Goal IV).

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 for understanding life as an emergent phenomenon in the context of organic chemical evolution. The appearance of life on a planetary body is the result of a series of abiotic chemical reactions whereby increasingly more complex organic molecules form from simpler ones, leading to the emergence of the first replicating organism. On Earth, this prebiotic process of organic chemical evolution culminated with an origin of life event. On Mars, the progress toward life might have terminated at different stages, or it might still be ongoing, depending on the physical and chemical constraints imposed by the environment. If mission analyses yield no definite evidence of life in environments that are or were likely capable of supporting prebiotic chemical reactions and preserving evidence of life, then it would become important to understand the nature and duration of such environments and the extent of organic chemical evolution they could have supported. This knowledge could offer new clues regarding the critical steps that lead to the first terrestrial organisms during a period of time that has been lost from the Earth's geologic record.

Delineating Objectives: Life in the continuum of organic chemical evolution

Life, when considered in a planetary context, is one end-member in the continuum of organic chemical evolution. In that respect the search for evidence of life and the assessment of abiotic organic chemical evolution are intimately linked. However, the strategies, technologies, target environments, and measurements involved in the search for evidence of life can be sufficiently distinct from those involved in assessments of organic chemical evolution that they are delineated into separate objectives.

For example, life displays emergent properties that have no counterpart in the abiotic world, such as the synthesis of complex structural, functional, and information-carrying molecules; elaborate cellular architectures and community fabrics; or complex behavioral responses. In addition, observations made by previous missions have identified a broad diversity of ancient sedimentary environments that could have supported abiotic organic chemical evolution and potentially life. Ancient sedimentary environments on Earth contain a biological record in the form of stromatolite structures and carbon isotope fractionations in kerogen. However, any molecular record of prebiotic organic chemical evolution appears to have been lost. Similarly, molecular evidence of abiotic organic chemical evolution in ancient sedimentary environments on Mars might have been lost to physical and chemical diagenesis, but evidence of life might have been preserved since the time of sediment deposition in the form of physical structures, stable isotopic abundances or other types of biosignatures that are comparatively more resistant to decay. On the other hand, the near-surface of Mars appears to be uninhabitable at present, but the same conditions that might impede biological activity (extreme cold and dryness) could favor the preservation of abiotic organic matter (exogenous and endogenous) that is sufficiently shielded from radiation. These are all instances that can be considered for distinct investigations of potential habitability, evidence of life and/or abiotic organic chemistry.

There might be cases where evidence of biological activity could overlap with abiotic organic chemistry. For example, degraded biomass could itself blend into abiotic-like chemistry; or exogenous sources of abiotic organic compounds (e.g., meteorites) could mix with biomass of an extant or an extinct biosphere. In such cases, investigations must take into account the issues of specificity, ambiguity, false positives, false negatives, and detectability. Despite the potential overlap in these specific cases, the distinction between life and organic chemical evolution is necessary in order to accommodate investigation strategies and environments that favor one but not the other. Thus, Goal I is divided into two objectives: one on the search for evidence of life (Objective A) and one on organic chemical evolution (Objective B), with priority on the former objective.

Prioritization

The discovery on Mars of signatures of life would spark a scientific revolution. The discovery of complex, abiotic organic chemistry would add to a growing body of evidence that the biochemical building blocks of terrestrial life might be universally available. Based solely on the potential to advance science, Objective A is given higher priority within Goal I.

Within Objective A, the search for evidence of life (Sub-Objective A1) must always be grounded on the likelihood that biosignatures could be expressed (Sub-Objective A2) and could be preserved (Sub-Objective A3). But prioritization between and within these sub-objectives must be case specific, as follows:

- In some instances, the body of information already acquired by the Mars Exploration Program might provide sufficient insights into habitability and preservation potential needed to inform a search for biosignatures[4]. At a minimum, empirical evidence of liquid water activity (Investigation A2.1) ought to satisfy a search for evidence of life <u>in the context of the duration, extent, and chemical activity of that liquid water</u>. In such instances, sub-objective A1 is given higher priority. We note, however, that a search for evidence of life must include a full assessment of habitability and preservation potential in order to place negative or ambiguous results in the right environmental context in order to interpret negative and ambiguous results based on their relevant environmental context.
- If empirical evidence of liquid water activity for a given environment is still lacking, then Sub-Objective A2 has the highest priority and becomes a necessary preamble to justify a search for evidence of life.
- Investigations within Sub-Objective A1 are ranked as "<u>High</u>" and "<u>Medium</u>" priority based largely on existing evidence of habitable conditions that is consistent with a search for chemical biosignatures (Investigation A1.1), structural biosignatures (Investigation A1.2) and physiological biosignatures (Investigation A1.3). This ranking can changed to reflect new discoveries, such as the discovery of a modern habitable environment that could sustain biological activity.
- Investigations within Sub-Objective A2 are ranked as "<u>High</u>" and "<u>Medium</u>" priority based on our current understanding of how the basic requirements for life are expressed on Mars. The availability of liquid water (Investigation A2.1) continues to be the great unknown for habitability, and investigations that address this knowledge gap are given high priority. All other investigations regarding habitability are given Medium priority.
- Investigations within Sub-Objective A3 are also ranked as "<u>High</u>" and "<u>Medium</u>" based on the priority conferred to biosignature Investigations in Sub-Objective A1.

Within Objective B, Sub-Objective B1 to characterize the atmospheric and crustal inventories of carbon and other bioessential elements is given highest priority, given the detections of variable atmospheric methane and organic matter in sedimentary deposits at Gale Crater. These results set a foundation on which to search for and characterize organic matter in other environmental settings, and directly assess the extent of abiotic organic chemical evolution on Mars. Within the context of Objective B, Investigation B1.1 (Characterize the inventory and abundance of organics on the martian surface, including macromolecular organic carbon, as a function of exposure time/age) is given the highest priority followed by Investigation B1.2 (Characterize the atmospheric reservoirs of carbon and their variation over time) and Investigation B1.3 (Constrain the abiotic cycling (between atmosphere and crustal reservoirs) of bioessential elements on ancient and modern Mars.) These particular investigations also overlap with several investigations in Goal II (e.g., Goal II: A2.2), highlighting their importance across goals.

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[4] Sufficiency in habitability and preservation potential assessment, as they bear on Goal I and Mars exploration, are discussed in detail in Appendix 3.

Goal I, Objective A: Search for evidence of life in environments that have a high potential for habitability and expression/preservation of biosignatures.

We have made great strides in our understanding of Mars in the past 20 years thanks to an ambitious and successful exploration program that included orbital and surface assets. One culminating achievement was the successful detection of organic matter in the ~3.6 billion-year-old sedimentary rocks in Gale crater by the Curiosity rover. This is an important milestone because it demonstrates that organic compounds can be preserved in the martian rock record for geologic timescales, and that there is potential that records of life's presence or abiotic chemical evolution are detectable.

Our knowledge of Mars would leap forward with the eventual analysis of samples returned to Earth for study. Planned for the next decade, samples would be collected and cached in Jezero crater, an environment that likely could have sustained life ~3.6 billion years ago. The discovery of evidence of life within those samples would motivate follow-up inquiries to understand the attributes of that life, what mechanisms underlie those attributes, how those attributes differ from terrestrial life and what was the sequence of events that lead to its origin.

If no evidence of life is discovered in the returned samples, that should not be taken as evidence that life never took a foothold on Mars. Attributes that make Jezero crater a compelling site for astrobiology exist in other regions where habitable environments, and potentially life, might have persisted before and also much later in Mars history, perhaps into the present. The MOMA instrument on ExoMars will search for signs of life in samples of Noachian clay-rich deposits to a depth of 2 meters, deeper than any previous mission. Results from these analyses will be directly relevant to Goal I, Objective A (and to Objective B). Further efforts to explore a broader parameter space of environments that were at some time habitable, including the subsurface, are indicated. The case for a potential subsurface biosphere is strengthened by the reports of liquid water ~1.5 km below the ice of the SPLD, and the low but seasonally-fluctuating levels of methane measured in the atmosphere (recognizing that subsurface aquifers have not yet been unambiguously identified, and that UV-alteration of meteoritic organics, subsurface reservoirs of ancient methane, and abiotic water/rock reactions could also be responsible for the methane signal).

Any search for evidence of life must stand on three legs, all equally important: *(1)* A search for biosignatures; *(2)* An assessment of habitability; and *(3)* An assessment of biosignature expression/preservation potential. The concepts of biosignatures, habitability and expression/preservation potential, as they bear on Goal I and Mars exploration, are discussed in detail in Appendix 3.

Goal I, Sub-Objective A1: Determine if signatures of life are present.

Investigations in this Sub-Objective are primarily focused on establishing, through in situ analyses of samples or analyses of samples returned to Earth, whether biosignatures exist on the surface or in the subsurface of Mars. Biosignatures can be broadly organized into three categories: chemical, structural, and physiological. Chemical biosignatures comprise organic and inorganic compounds whose presence, abundance, molecular structure, isotopic composition or function are affected by biological synthesis or biological activity. Structural biosignatures comprise physical objects whose morphology, shape, size, texture or fabric are affected by biological synthesis or biological activity. Physiological biosignatures are immediate manifestations of biological activity, such as rapid kinetics in chemical reactions, motion, growth or reproduction.

Forms of life that are biologically active can generate all three types of biosignatures. Forms of life that are dormant can generate chemical and structural biosignatures. Further, dormant life can be induced to generate physiological biosignatures. Forms of life that are dead can generate chemical and structural biosignatures, but not physiological ones. In all instances, biosignatures can degrade with time. Based on the types of biosignatures that can be expressed in each scenario (active, dormant, dead) Investigation A1.1 (chemical biosignatures) and Investigation A1.2 (structural biosignatures) are given higher priority. Investigations within this sub-objective overlap significantly with Sub-Objectives D2 and D4 in Goal IV.

<u>Goal I, Investigation A1.1:</u> Search for chemical signatures of life in surface or subsurface environments that have a high potential for modern/past habitability and expression/preservation of biosignatures. (High priority)

Example measurements: monomer abundances[5], enantiomeric[6] abundances, structure and composition of organic molecules, molecular-size distributions, stable isotopic abundances in possible organic/inorganic metabolic reactants and products, stoichiometry in elemental abundance of bioessential elements (e.g., C:N:P), chemical gradients; etc.

<u>Goal I, Investigation A1.2:</u> Search for physical structures or assemblages that might be associated with life in surface or subsurface environments that have a high potential for modern/past habitability and expression/preservation of biosignatures. (High priority)

Example measurements: Sedimentary structures and textures, size and shape of potential biominerals, size and shape of potential cell-like structures or cell-like assemblages, etc. These investigations ought to be combined with chemical and/or physiological information where possible.

<u>Goal I, Investigation A1.3:</u> Test for evidence of physiological activity in surface or subsurface environments that have a high potential for modern habitability. (Medium Priority)

Example measurements: Evidence of catalysis in chemically sluggish systems, reproduction, growth, motility, stable isotopic composition of possible metabolic reactants and products (i.e. metabolites).

Goal I, Sub-Objective A2: Investigate the nature and duration of habitability.

Investigations in this Sub-Objective are focused on establishing through remote sensing, in situ analyses of samples, or analyses of samples returned to Earth, the factors thought to influence habitability at different scales from local to global.

For investigations of recent or even modern habitability this requires understanding the present distribution and activity of liquid water near the surface and in the crust, and how it changes over time. For investigations of ancient habitability, the purpose of such investigations is to constrain the distribution of water in its various phases and geographic locations early in the history of the planet, based largely on clues contained in the geologic record. In all cases, assessments of habitability must also include 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

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[5] Monomers are molecules that can bond covalently to form a polymer such as amino acids, sugars and nucleobases

[6] Enantiomers are chiral molecules that are mirror images of each other, such as L/D-amino acids.

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.

Goal I, Investigation A2.1: Constrain the availability of liquid water with respect to duration, extent, and chemical activity across multiple spatial scales. (High priority)

Cross-cutting: Goal II; Goal III: A1; Goal IV: C2

For recent or modern habitability this includes assessments of freeze-thaw cycles in icy deposits within the upper crust and at the surface (including the polar caps), the possible formation of thin films of briny water near the surface, possible surface manifestations of subsurface liquid water (e.g., recurring slope lineae (RSL), gullies), and the presence of potential deep aquifers. The climate under the current and past orbital configurations tightly controls the distribution and physical state of water in the atmosphere and near the surface. As such, this Sub-Objective overlaps with Goal II, Objectives A and B as well as water-focused subobjectives in Goals III and IV.

For ancient habitability this includes geologic evidence for the location, volume, and timing of ancient water reservoirs as well as studies of the geologic record preserved in aqueous sediments and sedimentary deposits. An understanding of Mars' ancient climate is required to interpret the geologic record correctly, and therefore such investigations overlap with Goal II, Objective C and Goal III, Sub-Objective A1.

Example measurements: Presence of chemical sediments (e.g., salts, phyllosilicates) and their stratigraphic relations; measurements of stable isotopic composition of water ice; the distribution of soluble ions in the regolith; the distribution of subsurface water ice within and below 1 meter depth based on radar, neutron and other spectroscopies; distribution and extent of subsurface aquifers based on radar or seismic sounding; in situ electrochemical measurements of near-surface regolith.

Goal I, Investigation A2.2: Identify and constrain the magnitude of possible energy sources, chemical potential and flux. (Medium Priority)

Example measurements: Light spectrum and intensity, redox potential, Gibbs energy yield, presence of chemical red-ox couples in minerals and other chemicals.

Goal I, Investigation A2.3: Characterize the physical and chemical environment, particularly with respect to parameters that affect the stability of organic covalent bonds. (Medium Priority)

Cross-cutting: Goal III: A3

Example measurements: Temperature, pH, water activity, UV and ionizing radiation, redox potential, chaotropicity[7] etc.

Goal I, Investigation A2.4: Constrain the abundance and characterize potential sources of bioessential elements. (Medium Priority)

Cross-cutting: Goal III: A3

Example measurements: Presence and relative abundance of CHNOPS-bearing compounds, presence and relative abundance of micronutrients (e.g., Fe, Ca, Mg, etc.); sources and sinks of

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[7] Chaotropic compounds are soluble ions (e.g., Mg^{2+}, Ca^{2+}, ClO_4^-) that can disrupt the hydrogen bonding network between water molecules, thereby affecting the solubility of biopolymers.

trace gases (e.g., near-surface CH_4 and H_2), measurements of stable isotopic composition of CHNOPS-bearing compounds, micronutrients and trace gases.

Investigation A2.5: Provide overall geologic context. (Medium Priority)

Cross-cutting: Goal III: A2

Example measurements: Interdisciplinary data analysis (image, topographic, mineralogical, radar) that provides insight into the role of water in sediment mobilization processes, as well as the scale and magnitude of aqueous events; search for environmental indicator minerals through spectroscopy and high-resolution color imaging, especially in association with geomorphic expressions of water processes or reservoirs.

Goal I, Sub-Objective A3: Assess the preservation potential of biosignatures.

Investigations in this Sub-Objective are focused on establishing, through in situ analyses or analyses of samples returned to Earth, the potential of a given environment to preserve evidence of life from the time of measurement to the time when that environment was habitable. 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. 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. Important 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.

Goal I, Investigation A3.1: Evaluate conditions and processes that would have aided preservation and/or degradation of complex organic compounds, such as aqueous, thermal, and barometric diagenesis; chemical and biological oxidation; or radiolytic ionization. (High Priority)

Cross-cutting: Goal III: A2

Example measurements: Redox changes and rates in surface and subsurface environments (including determination of the effects of regolith and rock burial on the shielding from ionizing radiation); prevalence, extent, and type of metamorphism; potential processes that influence isotopic or stereochemical (i.e., the spatial arrangement of atoms in molecules) information, microscopic studies of rock samples.

Goal I, Investigation A3.2: Evaluate the conditions and processes that would have aided preservation and/or degradation of physical structures on micron to meter scales, such as physical destruction by mechanical fragmentation, abrasion, and dissolution; and protection by minerals (i.e., inclusions, surface bonding, grain boundaries). (High Priority)

Cross-cutting: Goal III: A2

Example measurements: Sedimentation rates, erosion rates; aqueous, thermal, and barometric diagenesis.

Goal I, Investigation A3.3: Evaluate the conditions and processes that would have aided preservation and/or degradation of environmental imprints of active metabolism such as chemical alteration or dilution. (Medium Priority)

Cross-cutting: Goal III: A2

Example measurements: Changes to stable isotopic composition and/or stereochemical configuration, enantiomeric racemization, documentation of instances including blurring of chemical or mineralogical gradients.

Goal I, Objective B: Assess the extent of abiotic organic chemical evolution.

While the highest priority objective is to determine whether or not life ever evolved on Mars, a secondary line of inquiry is to understand the degree of evolution of abiotic organic chemical systems in an environment that could sustain life. If life did not, in fact, emerge at any time in martian history, to what extent did Mars develop pre-biotic chemistry (as described in Appendix 3)? For example, is there evidence of pre-biotic[8] organic synthesis such as has been proposed for early Earth at hydrothermal vents? Is there evidence of development of amphiphilic[9] membranes derived from either exogenous materials or abiotic synthesis? Did abiotic chemical pathways that mimic biological metabolic pathways ever evolve? What processes have been responsible for fixation and transport of biologically important elements such as carbon and nitrogen on ancient and modern Mars? Recent detections of methane varying with time and location as well as macromolecular carbon in ~3.6 Ga rocks suggest both modern and ancient organic chemical evolution has occurred on Mars. What other evidence for abiotic organic processing exists in the unexplored regions of Mars, including the near and deep subsurface?

Life on Earth emerged from a feedstock of organic materials supplied by carbonaceous meteorites and also formed internally though geological and atmospheric reactions. The identification of similar organic building blocks on Mars, coupled with the knowledge of their formation/occurrence in a habitable environment would be a significant discovery, indicative that some of the foundational traits of Earth's biochemistry are, in fact, widespread in the solar system, and perhaps beyond. Discovery of these organic building blocks on Mars would also be a unique opportunity to investigate early stages of organic chemical evolution in a planetary setting, offering clues of the critical steps leading to the emergence of terrestrial organisms. The scientific significance of this opportunity cannot be understated, particularly since any evidence of these early stages of organic chemical evolution have been lost from Earth's geologic record. In addition, organic chemical evolution is constrained by the physical and chemical evolution of the planet, including the conditions of temperature, pressure, chemical composition and radiation below, above and on the surface, as a function of time. In this context, the process of organic chemical evolution on Mars is an integral aspect of the evolution of the planet.

Many of the investigations to answer these questions are by necessity identical to those proposed for Objective A. The search for prebiotic organics can overlap in many instances with the search for biogenic organics. The inherent challenge is discriminating abiotic versus biogenic sources of any organics detected, which is already required in order to address Objective A. In both the abiotic and biogenic cases, contextual measurements, whether we refer to them as "habitability" or as formation environment, are absolutely crucial in determining whether biotic or abiotic geochemical processes are responsible for organics. In characterizing the geological,

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[8] Here, the term "pre-biotic" refers to the poorly understood "messy chemistry" that bridges abiotic and biotic chemistry, with no assumption if life actually evolved.

[9] Amphiphilic compounds have both hydrophilic and hydrophobic parts (e.g., lipids)

physicochemical, and general environmental setting of a surface, atmosphere, or subsurface environment, we are cataloging the energy sources and raw materials present to drive abiotic organic synthesis and evolution.

Goal I, Sub-Objective B1: Constrain atmospheric and crustal inventories of carbon (particularly organic molecules) and other biologically important elements over time.

Investigations in this Sub-Objective are focused on establishing a thorough inventory of the atmospheric and crustal reservoirs of carbon and other biologically relevant elements, including both the feedstock or bulk starting materials available for organic synthesis and the complex organic products that may represent later stage organic evolution. The martian atmosphere is the largest reservoir of oxidized carbon, which cycles seasonally via sublimation and condensation at the poles. Information about the history of the atmospheric reservoir of carbon is contained in the form of carbonate that has been detected both in situ and with orbital remote sensing in multiple surface locations. Nitrogen is present as N_2 gas in the atmosphere and as chemically available nitrate in the regolith. Sulfur is present in both reduced and oxidized forms and has actively cycled between the atmosphere and crust over the length of martian history. Carbonates, nitrates, and sulfates in surface materials serve as the link between the atmospheric and crustal reservoirs of these species. Understanding how the reservoirs of these biologically relevant materials have changed over time is important for our understanding of what materials were available for abiotic and potentially pre-biotic chemistry on Mars.

The handful of organic detections in martian materials range widely in complexity, from methane in the atmosphere to reduced macromolecular carbon in basalts. In addition, both simple and macromolecular organics have recently been detected in ~3.6 Ga sedimentary rocks. Mars surface materials also produce CO_2 during thermal decomposition, which could be from decarboxylation of simple carbon compounds or oxidation of reduced carbon. The Mars surface should also harbor complex organic molecules from meteoritic infall. As in situ measurement strategies and instrumentation become increasingly mature, we will continue to add to these detections of Mars organics and better understand their association with inorganic reservoirs.

<u>Goal I, Investigation B1.1:</u> Characterize the inventory and abundance of organics on the martian surface, including macromolecular organic carbon, as a function of exposure time/age. (High Priority)

Example measurements: Monomer abundances, enantiomeric ratios, structure and composition of organic molecules, and molecular-size distributions of organic molecules in Mars surface materials, with corresponding exposure age estimates from either in situ geochronology or relative dating methods, variability of stable isotopic composition of organic and carbonate phases.

<u>Goal I, Investigation B1.2:</u> Characterize the atmospheric reservoirs of carbon and their variation over time. (High Priority)

Cross Cutting: Goal II: A1.2, A2, B3.1; Goal III: A3.4

Example measurements: Variations in methane atmospheric abundance and isotopic composition, detection of trace abundances of volatile and possible aerosol/dust organics.

<u>Goal I, Investigation B1.3:</u> Constrain the abiotic cycling (between atmosphere and crustal reservoirs) of bioessential elements on ancient and modern Mars. (Medium Priority)

Cross Cutting: Goal II: A2, C1.2, C1.3; Goal III: A3.4

Example measurements: Abundance of reduced nitrogen and sulfur species in surface materials and Mars meteorites, isotopic compositions of reduced and oxidized species (particularly C, H, N, O, and S), trace gas abundance variation over time.

Goal I, Investigation B1.4: Characterize bulk carbon in martian mantle and crust through investigations of martian meteorites. (Medium Priority)

Cross Cutting: Goal III: B1.1

Example measurements: Complexity, diversity, abundance, and stable isotopic composition of carbon-bearing phases in Mars meteorites.

Goal I, Sub-Objective B2: Constrain the surface, atmosphere, and subsurface processes through which organic molecules could have formed and evolved over martian history.

Investigations in this Sub-Objective are focused on identification of potential mechanisms responsible for organic synthesis and evaluation of their presence in the martian atmosphere and crust. For example, zones of liquid water in the near surface and deep subsurface provide the most likely environments to sustain prebiotic organic chemistry. Wet/dry cycles in ice-bearing regolith caused by changes in temperature or in salt deposits caused by changes in humidity could lead to polymerization reactions of amino acids and other molecular building blocks, provided the individual monomers are present. In the subsurface, water-rock interactions associated with serpentinization could drive organic synthesis. Mineral surface catalyzed reactions have been experimentally shown to be effective in adding carboxyl groups and lengthening carbon chains. Atmospheric reactions such as photolysis may also participate in the synthesis of simple organic molecules that may be recorded in surface materials. Investigations in this Sub-Objective may be achieved by laboratory experimental simulations as well as in situ measurement campaigns.

Goal I, Investigation B2.1: Investigate atmospheric processes (e.g., photolysis, impact shock heating) that could potentially create and transform organics. (High Priority)

Example measurements: Light spectrum and intensity, effects of radiation on organics.

Goal I, Investigation B2.2: Investigate the role of ionizing radiation in organic synthesis and destruction. (High Priority)

Example measurements: Ionization radiation, characterization of organic inventory and abundance as a function of depth and exposure age as characterized by in situ geochronology or relative dating methods.

Goal I, Investigation B2.3: Investigate surface and near-surface processes, such as mineral catalysis, that play a role in organic evolution. (Medium Priority)

Example measurements: Mineral-organic co-occurrence and relationships, trace and major element geochemistry.

Goal I, Investigation B2.4: Investigate the role of subsurface processes (e.g., hydrothermalism, serpentinization) in driving organic evolution. (Medium Priority)

Example measurements: Characterize mineral assemblages to understand water rock ratios and alteration temperatures, inventory organic abundance and distribution in subsurface materials.

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

Objectives	Sub-Objectives
A. Characterize the state and controlling processes of the present-day climate of Mars under the current orbital configuration.	A1. Characterize the dynamics, thermal structure, and distributions of dust, water, and carbon dioxide in the lower atmosphere.
	A2. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs.
	A3. Characterize the chemistry of the atmosphere and surface
	A4. Characterize the dynamics and thermal structure of the upper atmosphere and magnetosphere.
B. Characterize the history and controlling processes of Mars' climate in the recent past, under different orbital configurations.	B1: Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions.
	B2: Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of low- and mid-latitudes.
	B3: Determine how the chemical composition and mass of the atmosphere changed in the recent past.
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 and interpret surface records of past climates and factors that affect climate.

The fundamental scientific questions that underlie Goal II concern how the climate of Mars has evolved over time to reach its current state, and the present and past processes that control climate. This is a subject of intrinsic scientific interest that also has considerable implications for comparative planetology with Earth and other terrestrial planets, in the solar system and beyond.

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. For convenience, the climate history of Mars can be divided into three different states: *(i)* Present climate, operating under the current orbital parameters and observable today; *(ii)* Recent past (i.e. < ~5-50 Myr) 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 strongly enhances our confidence in our understanding of the climate in the recent past. Furthermore, since not all climate processes leave a distinctive record, it is also necessary to determine which climate processes may have recorded 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 important 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, Goal II is organized around three objectives, each pertaining to the different climate epochs. Investigations within a sub-objective are assigned a prioritization of higher, medium, or lower. This prioritization is based on subjective weighting that includes: consideration of existing measurements with respect to new measurements needed to advance knowledge; relative contribution of an investigation towards achieving an objective; tractability; and identification of investigations with logical prerequisites. Importantly, the investigation prioritization is only with respect to the investigations within the parent sub-objective. The sub-Objectives are in turn assigned a subjective prioritization of higher or medium that reflects the net priority of the investigations within a sub-objective. The objectives are not prioritized relative to each other, as each are needed to understand how and why the climate of Mars (and of similar terrestrial planets with atmospheres) has changed through time.

Goal II, Objective A: Characterize the state and controlling processes of the present-day climate of Mars under the current orbital configuration.

The chemistry, dynamics, and energetics of the present martian atmosphere are all of key importance to understanding the present-day climate system. Characterizing the present-day atmosphere also helps to inform our understanding of the recent past and ancient climate. The present-day climate controls the distribution and physical state of water in the atmosphere and near the surface, which is important for habitability (Goal I). Finally, characterizing the present atmosphere aids robotic mission planning and preparation for the arrival of humans (Goal IV).

The climate system consists of many coupled subsystems, including atmospheric, surface, and near-surface reservoirs and the exchanges between them of CO_2, H_2O, and dust. While it is convenient to distinguish the lower atmosphere, the upper atmosphere, and the surrounding plasma environment as distinct regions, there are energy, momentum, and mass transfers between them. The regions are therefore strongly interconnected, though the driving processes in each are different. Well-planned measurements of all of these regions enable characterization of the physical processes that control the present and past climates of Mars.

Objective A will be achieved most effectively by a combination of observations, modeling, and laboratory experiments. Numerical modeling of the atmosphere is critical to understanding atmospheric and climate processes. Models provide dimensional and temporal context to necessarily sparse and disparate observational datasets, particularly when combined with data assimilation techniques, and constitute a virtual laboratory for testing whether observed or inferred conditions are consistent with proposed processes. Laboratory experiments allow controlled investigations of specific processes under conditions where the system of interest is too complex to allow numerical modeling.

Goal II, Sub-Objective A1: Characterize the dynamics, thermal structure, and distributions of dust, water, and carbon dioxide in the lower atmosphere. (Higher Priority)

Knowledge of the processes controlling distributions of dust, water, and CO_2 may be arrived at by direct observations (in-situ or remote) of these substances, and by observation of the atmospheric state, circulation, and its associated forcings. Although major advances have been made, particularly by remote sensing from orbit, more complete diurnal coverage and observations of the time-varying three-dimensional 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 and 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 condensation/sublimation) to these forcings over daily, seasonal, and multi-annual timescales.

New measurements such as remotely-derived wind velocity would also advance this Sub-Objective, but to maximize scientific return such measurements must be combined with simultaneous basic observations to provide context and elucidate responsible processes. Future orbital mission concepts that are motivated by this Sub-Objective should therefore seek to provide new measurements (e.g., wind) or significantly improve spatial and temporal coverage and resolution beyond the existing data and ideally span multiple Mars years to capture the full range of variability of the current Mars weather and climate.

Obtaining a high quality dataset from a properly accommodated surface-based weather station (i.e., one in which thermal and mechanical contamination from the spacecraft is minimized beyond what has been done previously) is still of highest priority. Any proposed measurement of in situ meteorological parameters needs to 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.

The transition from single to multiple simultaneous datasets simultaneously collected from multiple locations and/or over multiple times of day would enable a major advance in our understanding of martian weather and climate. This could be achieved via a single dedicated multi-lander mission, or a commitment to include standardized weather instrumentation on all future landers, or both. Obtaining high quality datasets from multiple networked surface weather stations or potentially aerial platforms would constitute a major advance for this Sub-Objective, providing vital ground-truth validation for complementary measurements retrieved from orbit and essential data for designing and validating climate and weather model parameterizations. Measurements at multiple sites are required to determine the applicability of measurements and physical process parameterizations to different martian environments (e.g., polar and non-polar; upwind and downwind of major topography).

The scientific results of this Sub-Objective have substantial relevance to engineering aspects of the exploration of Mars (Goal IV).

Goal II, Investigation A1.1: Characterize the dynamical and thermal state of the lower atmosphere and their controlling processes on local to global scales. (Higher Priority)

Cross-Cutting: Goal I: B1; Goal II: A1.2, A4.1

This Investigation focuses on the state of the atmosphere and its response to forcing. Measurements on a wide range of spatial scales are important:

- Turbulent (micro) scale: Measurements of pressure (p), temperature (T), wind (V), and water vapor (RH), together with the measurement of turbulent fluxes of heat and momentum at a variety of sites at different seasons.
- Mesoscale: Measurement of the same 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. High-quality wind measurements are generally absent. Boundary layer measurements of winds, made simultaneously with temperature and pressure, remain a high priority. New and improved measurements generally are considered to be of higher priority than those that would only extend existing data, as they are more likely to result in a substantial rather than incremental advance in knowledge. For example, continuing global measurements of column water abundance would be good, but capturing its vertical profile as well (even during dust storms!) would be better; a landed meteorological payload that measures only temperature and pressure would be helpful, but the additional measurement of winds and turbulent fluxes could be paradigm shifting.

Effective characterization of mesoscale circulations requires experiments to measure fundamental parameters both at the surface and in the vertical in multiple topographic contexts (e.g., plains versus craters versus valleys). Meteorological observations gathered on daily- to decade-long timescales characterize larger-scale circulations (e.g., baroclinic eddies and the thermal tide), and inter-annual and long-term trends in the present climate system. Importantly, long-term measurements provide a means to characterize the cycling of volatiles, condensates, and dust on a range of timescales. Measurement of non-condensable 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 (Objective B). Finally, 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.

Measurement of the forcing mechanisms of the atmosphere can be grouped into three categories: the surface energy balance, the momentum budget, and the atmospheric energy budget. The surface budget, which has not yet been comprehensively measured, is composed of insolation, reflected light, incoming and outgoing infrared radiation (IR), turbulent fluxes, energy conducted to/from the surface, and possible condensational processes. Wind/momentum measurements in the atmosphere other than at the surface are still absent. To date, the atmospheric momentum fields have been diagnosed from the thermal structure assuming dynamical balance. This is problematic for the boundary layer, and independent wind measurements could reveal model deficiencies for the deep atmosphere as well. Measurement of winds (momentum) at the surface and throughout the lower atmosphere is a high priority within this Investigation and within this Sub-Objective as a whole.

Goal II, Investigation A1.2: Measure water and carbon dioxide (clouds and vapor) and dust distributions in the lower atmosphere and determine their fluxes between polar, low-latitude, and atmospheric reservoirs. (Higher Priority)

Cross-Cutting: Goal IV: B2

Dust and clouds (H_2O and CO_2 ice) are the major radiatively active aerosols of the present-day 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 less well known, but also appear complex and show evidence of coupling to the dust cycle. 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 the following areas:

- Vertical, horizontal and temporal variations
- Physical and optical properties
- 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. It is also potentially relevant for electrochemical processes. Vertical structure and physical properties are the highest priority in this list.

Goal II, Sub-Objective A2: Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs. (Higher Priority)

Current 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 PLD, and how these reservoirs influence the present climate.

Knowledge of the processes that control the lifting of dust from the surface and into the atmosphere is also insufficient. The most fundamental processes for dust lifting are thought to be the shear stress exerted by the wind onto a dusty surface, and ejection due to saltation of sand-sized particles over a dusty surface. Furthermore, rapid pressure changes associated with dust devils and/or electrostatic forces may be important. In the south polar region, dust injection by seasonal CO_2 jets is still poorly characterized and may be significant.

Goal II, Investigation A2.1: Characterize the fluxes and sources of dust and volatiles between surface and atmospheric reservoirs. (Higher Priority)

Cross-Cutting: Goal II: A1.1; Goal III, A2.2; Goal IV

This includes:

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

Measurements of turbulent fluxes provide a direct link to sand and dust lifting. Once the turbulent wind stress is known, however, 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.

Dust may be lifted by dust devils, directly by winds, or via saltation. If saltation is an important lifting mechanism on Mars, as it is on Earth, then the spatial, temporal, and size distribution of both the dust itself and of sand-sized particles is important. Understanding of the lifting processes and source distribution are vital for simulating the dust cycle and dust storms on multi-annual timescales. Current limitations in our understanding of the dust cycle impacts many aspects of robotic and eventual human mission operations (Goal IV) on Mars, with solar power generation a particular concern.

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 also of relevance to this Investigation. Grain charging is tied to the dust lifting and saltation process, and electric fields may play a role in dust lifting, particularly within dust devils.

Goal II, Investigation A2.2: Determine how the processes exchanging volatiles and dust between surface and atmospheric reservoirs affect the present distribution and short-term variability of surface and subsurface water and CO_2 ice. (Higher Priority)

Cross-Cutting: Goal I: A2, B1.4; Goal II: B1, B2; Goal III: A1; Goal IV: C2

Water ice has been detected at many locations and depths on Mars. 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 SPLD. The current distribution of these materials is not in equilibrium with the environment, which suggests that they were emplaced under different climatic conditions (see Objective B).

Large-scale sub-surface water ice deposits exist at mid- and high-latitudes in both hemispheres and may buffer long-term surface-atmosphere exchange. The current equilibrium state between the subsurface water ice and the atmosphere is unknown. Assessment of net accumulation or loss of the residual ice deposits and the seasonal ice as a function of location and time are important components of this Investigation. Measurements that quantify the rate at which water vapor diffuses between subsurface water ice and the atmosphere are also needed. 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 and longer timescales, and therefore require long-term monitoring. Better characterization of present-day processes operating to alter the PLD are also relevant to this Investigation.

The current martian seasonal cycle is dominated by condensation and evaporation of ~1/3 of the carbon dioxide atmosphere into the seasonal caps. 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 cap persists for many months during the polar night, but at its lowest latitudes the cap experiences diurnal forcing that causes 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 complete this Investigation, it is necessary to determine the distribution of H_2O and CO_2 frost deposition and loss on diurnal to multi-annual timescales.

Finally, little is currently known about the long-term trends in accumulation/loss of the permanent caps and PLD. The mass balance depends on surface absorption/reflection and volatile phase changes, including sublimation, direct deposition, and precipitation. Constraining these processes, ideally in situ, will allow this question to be tackled.

Goal II, Sub-Objective A3: Characterize the chemistry of the atmosphere and surface. (Medium Priority)

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 three-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, the importance of electrochemical effects, which may be 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. In particular, the curious case of methane (detected at the surface in Gale Crater but not in the free atmosphere) has yet to be resolved. In situ measurements by the Mars Science Laboratory mission (MSL/*Curiosity*) indicate background levels of ~1 ppb, with temporary excursions of up to ~7 ppb have been found. At the same time, ESA's Trace Gas Orbiter (TGO) has thus far failed to detect methane from orbit.

Advances in this Sub-Objective will require global orbital observations of neutral and ion species, temperatures, and winds in the lower and upper atmospheres (see Sub-Objectives A1 and A2 in this Goal), 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. The eventual return of atmospheric and surface samples to Earth for in-situ analysis also has the potential to advance this Sub-Objective significantly.

Goal II: Investigation A3.1: Measure the global average vertical profiles of key gaseous chemical species in the atmosphere and identify controlling processes. (Higher Priority)

Cross-Cutting: Goal I: A2, B1, B2

The key species of interest are:

- 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^-.

The vertical profiles of species arise from the coupled interaction of photochemistry with vertical mixing occurring on a range of spatial scales. Photochemical models predict these profiles, and measurements provide one of the most direct ways to validate and test photochemical reaction rates and pathways, and to test model assumptions about vertical mixing.

Goal II, Investigation A3.2: Measure spatial and temporal variations of species that play important roles in atmospheric chemistry or are transport tracers and constrain sources and sinks. (Medium Priority)

Cross-Cutting: Goal I: A2, B1, B2

The key species of interest are:

- 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.

Goal II, Investigation A3.3: Determine the significance of heterogeneous reactions and electrochemical effects for the chemical composition of the atmosphere. (Medium Priority)

Cross-Cutting: Goal II: A3.1, A3.2

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 generally is considered a prerequisite to this Investigation, so its prioritization is ranked lower accordingly.

Electrochemical effects may also be important for production of certain species (e.g., H_2O_2) and promoting surface-atmosphere reactons, but confirmation is needed. Successful characterization of electrochemical effects 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.

Goal II, Sub-Objective A4: Characterize the dynamics and thermal structure of the upper atmosphere and magnetosphere. (Medium Priority)

The boundary between the lower and upper atmosphere is an imprecise concept. The mesopause, around 90 km, provides a convenient choice with regard to thermal structure. Below it, chemical composition is relatively stable and visible and IR wavelengths dominate radiative heating. Above it, and particularly above the spatially and temporally variable homopause and turbopause around 110 km, chemical composition varies with altitude and ultraviolet (UV) and shorter wavelengths dominate radiative heating. Remote sensing and in situ sampling by missions like MAVEN and Mars Express (MEx) reveal complex spatial and temporal variations in the dynamics and thermal structure of the upper atmosphere and surrounding plasma environment, but the observations are limited in time and space, so are not yet sufficient to determine how processes distribute momentum and energy throughout the atmosphere system.

In the upper atmosphere, both neutral and ionized species are present and influence the behavior of the 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. 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 systematic, near-synoptic 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>Goal II, Investigation A4.1:</u> Characterize the mechanisms for vertical transport of energy, volatiles, and dust between the lower atmosphere and the upper atmosphere. (Higher Priority)

Cross-Cutting: Goal I: A2

The upper atmosphere and lower atmosphere of Mars are in close communication. Mass is exchanged between the two regions: both ablated infalling planetary dust and captured solar wind helium may be a source of trace gases for the lower atmosphere, and trace gases such as hydrogen diffuse from the lower atmosphere, populating the exosphere and escaping to space. There is now strong evidence that hydrogen escape is seasonally variable, limited by the amount of atmospheric heating such as during major dust storms. Gravity waves and tides observed in the upper atmosphere demonstrate that the lower atmosphere is a source of energy for the thermosphere.

There is a paucity of measurements of the transition region from the lower atmosphere to the upper atmosphere, an area difficult to model because of the different physics and timescales that are important for the two regimes. Much remains to be understood about the transfer of energy and volatiles from below, and the sources and fates of dust inferred to occupy the upper atmosphere. There is significant overlap between this Investigation and the contents of Sub-Objective C1 of this Goal, as understanding this region today is essential to extrapolating back into the past.

<u>Goal II, Investigation A4.2:</u> Characterize the spatial distribution, variability, and dynamics of neutral species, ionized species, and aerosols in the upper atmosphere and magnetosphere. (Lower Priority)

Cross-Cutting: Goal I: A2; Goal IV: A1

Due to their radiative properties, aerosols can markedly affect upper atmospheric temperatures, and hence density distributions. Observations show strong seasonal and spatial variations in the abundances of aerosols in the upper atmosphere, but coverage is incomplete and variability in abundance and physical properties with local time is not well-constrained.

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. Prior to the arrival of the Mars Atmospheric and Volatile Evolution mission (MAVEN), there had been few measurements of the densities of major neutral species in the upper atmosphere. These species are now regularly being measured from solar moderate to minimum conditions, but again the time-space coverage and variability, particularly as related to transport from below and solar forcing from above, is presently inadequate to test fully models of upper atmospheric processes, including escape.

Because ionized species in the upper atmosphere generally are derived from neutrals, the behaviors of neutrals and ions are tightly linked. Ion measurements by orbiting spacecraft, such as MAVEN, reveal a rich ion chemistry with dawn/dusk and day/night asymmetries. Electron densities in the upper atmosphere have been measured using radio occultation and radar. Electron measurements over strongly magnetized regions suggest very complex spatial density distributions that have yet to be comprehensively explored. More observations are required to fully characterize these ion and electron distributions and the interactions that produce them.

Goal II, Investigation A4.3: Characterize the thermal state and its variability of the upper atmosphere under the full range of present-day driving conditions. (Lower Priority)

Cross-Cutting: Goal I: A2; Goal IV: A1

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. A number of recent measurements from the MAVEN mission have allowed forward progress in understanding the thermal state and dynamics of the upper atmosphere. In situ ionospheric electron density and temperature measurements are being made regularly, as are measurements of the temperatures of major ionospheric and thermospheric species. Neutral winds are also being observed, and some ionospheric currents are being indirectly inferred from magnetic field observations. Differences in temperature and currents have been noted in regions of crustal magnetic fields.

Despite these measurements, large gaps remain in the parameter space covered by observations. Perhaps the most notable omission is the measurement of temperatures and dynamics at solar maximum, although variations in temperature and dynamics are expected over solar-rotation, seasonal, and shorter timescales as well. Further, ion velocity measurements remain a work in progress below the exobase. Connection of these measurements to forcing mechanisms of the upper atmosphere (solar irradiance, solar wind and magnetospheric conditions, and coupling with the lower atmosphere) has not yet been made. The MAVEN mission should be able to satisfy much or all of this objective if it can continue to observe over a solar cycle. Gaps in time-space coverage will remain, however.

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

Changes in Mars' obliquity in the geologically recent past should enhance the transfer of volatiles between the atmosphere and reservoirs in the surface and sub-surface, thereby changing the mass of the atmosphere and redistributing materials (e.g., subliming or adding CO_2 ice such as that buried in the south polar cap) across and beneath the surface. It is also possible that such changes could have occurred under the current orbital configuration if CO_2 was exchanged between the atmosphere and the condensed reservoir that has been reported buried near the south pole. Changes in the atmospheric mass due to partial collapse or augmentation of atmospheric CO_2 onto the surface would have affected the atmosphere's composition, thermal structure, and dynamics. Changes in orbital parameters would also affect the thermal state of surface and near-surface water ice. Under certain circumstances, ice in the top 1 meter could have melted, potentially creating a habitable environment (Goal I: A2).

Many geological features that formed in the recent past are available for interpretation today, and likely contain information about the climate under which they formed. This information can be used to validate models for recent climate evolution at Mars, which can in turn be used to extrapolate 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 PLDs 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 (Goal III).

Goal II, Sub-Objective B1: Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions. (Higher Priority)

The polar regions have been shaped by the climate of the recent past, as changing obliquity has redistributed volatiles between the atmosphere and the surface and sub-surface. Our understanding of how and to what extent this redistribution has occurred is incomplete. For example, it is unclear how materials are sequestered and maintained through large-scale climatic changes.

Extensive layered deposits in the polar regions (i.e., the PLD) 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 redeposited 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; and solar luminosity (extracted by comparisons with terrestrial ice cores). 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).

While it is critically important to understand the processes by which the PLD were produced, the climate record in the polar regions is not restricted to the PLD. Multiple units in both the northern and southern hemisphere polar regions likely predate and overlap (in time) the formation of the NPLD, and thus bridge ancient climate and geologic records to more recent ones. Addressing this Sub-Objective will require in situ and remote sensing measurements of the stratigraphy and physical and chemical properties of the polar units.

<u>Goal II, Investigation B1.1:</u> Determine how orbital parameters, atmospheric processes, and surface processes influence layer formation and properties in the polar regions. (Higher Priority)

Cross-Cutting: Goal III: A1, A3

The extent to which physical, chemical, and compositional properties of polar units are influenced by specific processes that occur there are poorly understood. For instance, the abundance of dust in a particular layer may indicate the deposition rate of dust at the time of layer formation, or it may be the result of a dust lag enhancement initially formed during sublimation and cap erosion. The operation of the dust cycle, the frequency and phasing of dust storms, and the resulting availability of dust under different orbital configurations are not well constrained by observations or by models (which at present must impose an atmospheric dust distribution). Other processes for ice deposition and sublimation are similarly poorly constrained for the recent past. The need is to understand the relative contributions of deposition and erosion, and the factors controlling each, in order to determine how layers and icy deposits are formed and expressed today and how to extrapolate that knowledge into the past.

Once the processes that influence the polar units are well understood, fundamental atmospheric properties in climate models, such as atmospheric mass, can be varied until that the predicted properties of polar icy deposits best reproduce observations. Finding agreement between observations and model predictions would then suggest a constraint for the absolute ages of specific layers in the PLD, for example. 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.

<u>Goal II, Investigation B1.2:</u> Determine the vertical and horizontal variations of composition and physical properties of the materials forming the Polar Layered Deposits (PLD). (Higher Priority)

Cross-Cutting: Goal III: A1, A3

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 redistribution and mineral sources.

<u>Goal II, Investigation B1.3:</u> Determine the absolute ages of the layers of the Polar Layered Deposits (PLD). (Medium Priority)

Cross-Cutting: Goal I: A2; Goal III: A1, A3

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.

Goal II, Sub-Objective B2: Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of low- and mid-latitudes. (Medium Priority)

Our understanding 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. Their ages 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. It has strong synergies with Goal IV, Sub-Objective D1, which requires the characterization of extractable water resources for human in situ resource utilization (ISRU). It is connected to Goal I, Sub-Objective A2, which is focused on the nature and duration of habitability. It also has many natural connection points to the Objectives outlined in Goal III.

<u>Goal II, Investigation B2.1:</u> Characterize the locations, composition, and structure of low and mid-latitude ice and volatile reservoirs at the surface and near-surface. (Medium Priority)

Cross-Cutting: Goal I: A2; Goal III: A1, A3; Goal IV: D1

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 yet 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>Goal II, Investigation B2.2:</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)

Cross-Cutting: Goal I: A2; Goal III: A1, A3

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.

Goal II, Sub-Objective B3: Determine how the chemical composition and mass of the atmosphere has changed in the recent past. (Medium Priority)

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 the global volatile budget and dominant drivers (e.g., different surface pressure conditions). 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.

Addressing 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.

<u>Goal II, Investigation B3.1:</u> Determine how and when the buried CO_2 ice reservoirs at the south pole formed. (Medium Priority)

Cross-Cutting: Goal I: B1; Goal III: A1, A3

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 epochs under which these deposits formed, and the processes responsible, will provide valuable new information about recent changes in the martian climate.

<u>Goal II, Investigation B3.2:</u> Measure the composition of gases trapped in the Polar Layered Deposits (PLD) and near-surface ice. (Lower Priority)

Cross-Cutting: Goal III: A1, A3

Terrestrial ice cores have provided invaluable information 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. Thus, layers in the PLD will record compositional variability. Despite the high scientific value of ice core measurements at Mars, this Investigation is designated as lower priority because of tractability; it is currently perceived as a difficult measurement requiring significant technology development, and possible precursor missions.

Goal II, 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, with significantly more surface erosion and chemical alteration by liquid water and habitable surface conditions on timescales that continue to be debated. Explaining this abundant evidence for liquid water is an ongoing challenge in light of Mars' more distant orbit and the likely faintness of the young Sun. An understanding of Mars' ancient climate is required to interpret the geologic record correctly and to determine the best environments in which to search for signs of ancient life. It is also of great importance for comparative planetology and for improving our ability to make testable predictions of the atmospheric evolution and habitability of exoplanets.

Characterizing Mars' ancient climate requires interdisciplinary study of the martian surface and atmosphere. There is currently high uncertainty about many of these details, including the composition and mass of the ancient atmosphere through time, the planet's topography and degree of true polar wander and the contribution of non-atmospheric processes to warming and melting of liquid water. Additional uncertainties remain in the evolution of Mars' magnetic field and the output and variability of the young Sun. Multiple atmospheric, geologic and external planetary constraints must therefore be investigated in parallel to develop a self-consistent picture of the climate evolution of Mars over the entire timespan constrained by its geologic record.

Goal II, Sub-Objective C1: Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present. (Higher Priority)

The state of the martian atmosphere through time can be constrained by characterizing source and sink terms and by analyzing the chemical composition of ancient rocks. High-precision radiometric dating and isotopic measurements of martian meteorites and returned samples can be used to constrain atmospheric properties at the time of the sample's formation. Some similar measurements may also be performed in situ by landers. The most important sources of the martian atmosphere are volcanism, bolide impacts and crustal alteration, while the key sink terms are deposition of volatiles and minerals on the surface, and escape to space. Each of these terms must be investigated separately to build up an accurate process-based picture of the change in the atmosphere with time.

Goal II, Investigation C1.1: Measure the composition and absolute ages of trapped gases. (Higher Priority)

Cross-Cutting: Goal III: A3

Trapped gases in rock samples provide a potentially powerful way to directly measure the composition of the ancient martian atmosphere. When determination of absolute ages is also possible, this strongly enhances the value of the derived data. Samples covering key periods of martian history, from the pre-Noachian to the Amazonian, hold the potential to significantly advance our understanding of martian climate evolution. This Investigation is of high priority for in situ dating and analysis investigations and should be a central component of any sample return mission. Studies of the feasibility of specific analysis approaches, ideally with reference to established methodologies in Earth science, are an important near-term goal that also fall within the scope of this Investigation.

Goal II, Investigation C1.2: Characterize mineral and volatile deposits to determine crustal sinks of key atmospheric species. (Medium Priority)

Cross-Cutting: Goal I: B1.4; Goal III: A1

While characterization of the atmosphere through direct analysis of geologic samples will be a potentially very powerful way to obtain constraints on composition through time, important progress can also be made by a process-based approach. The key sinks of atmospheric gases are formation of crustal minerals and escape to space. The extent of crustal sinks can be estimated by determining total mineral and volatile deposits. This Investigation can be partially achieved by orbital investigation of surface volatile and mineral inventories. Determination of the mineral inventory in the deep crust will remain a challenge for the foreseeable future, but any studies that propose innovative approaches to make progress on this problem fall within the scope of this Investigation.

Goal II, Investigation C1.3: Determine sources of gases to the atmosphere over time by characterizing rates of volcanism, crustal alteration, and bolide impact delivery. (Medium Priority)

Cross-Cutting: Goal I: B1.4; Goal III: A1, B1.1

Volcanism, crustal alteration (particularly in the presence of liquid water) and bolide impacts constitute the key sources of gases to the martian atmosphere through time. Better characterization of the volatile inventory and chemistry of the martian mantle (particularly the redox state / oxygen fugacity), ideally with multiple samples to investigate heterogeneity, are required to characterize the chemistry of martian outgassing. Better characterization of martian geodynamics through time is needed to constrain models of mantle evolution and tectonics, which determines volcanic outgassing rates. To constrain crustal gas sources, particular attention must be paid in orbital, in situ, and return-sample analysis of mineral products (such as serpentine) whose formation is known to be associated with the emission of radiatively important gases (such as hydrogen). Constraints on the importance of bolide impact gas delivery and removal can be obtained by detailed in-situ study of the mineralogy of impact crater terrain, by tighter characterization of impactor fluxes through time, and by modeling of key impact processes. There is significant overlap between this Investigation and the contents of Goal III, Objectives A and B.

Goal II, Investigation C1.4: Determine the rates of atmospheric escape over geologic time. (Medium Priority)

Cross-Cutting: Goal I: A2; Goal III: A3

Detailed knowledge of present escape processes enables estimates of the evolution of the atmosphere in the recent past, when other source and sink terms have been less important. The accuracy of escape estimates obtained from measurements by spacecraft missions such as MAVEN and Mars Express (MEx) decreases as they are extrapolated further back in time due to quantitative and qualitative changes in the driving processes, but this still provides a vital way to constrain deep-time evolutionary models against observations. Observations and validated models show that escape rates of key species vary spatially (e.g., due to crustal magnetic fields), seasonally (e.g., due to the water cycle and dust storms), and in response to changes in the solar output. 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 are needed to capture the inter-annual and solar cycle variability induced by these effects. Addressing this Investigation will require global orbital observations of neutral and plasma species, temperatures, and winds in the extended upper atmosphere, as well as complementary observations and models of the state of the solar wind, magnetosphere, and magnetic field over time, which strongly influence escape processes.

Goal II, Sub-Objective C2: Find and interpret surface records of past climates and factors that affect climate. (Higher Priority)

The geomorphology and geochemistry of Mars' surface records information about the planet's climate evolution. 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 is a key constraint on the evolution of the ancient climate. Analysis of the relevant physical and chemical records can 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 through time are also important to the ancient climate. Addressing this Sub-Objective will require the application of geological techniques, including determination of sedimentary stratigraphy and the spatial and temporal distribution of aqueous weathering products, to climate-related questions. There is significant overlap between this Sub-Objective and the contents of Objective A of Goal III, with the latter focused on the geologic record preserved in the crust as opposed to the climate record.

<u>Goal II, Investigation C2.1:</u> Constrain the early water cycle by determining the spatial extent, age, duration, and formation conditions of ancient water-related features. (Higher Priority)

Cross-Cutting: Goal III: A1

Improved characterization of water-related surface features (both geomorphic and geochemical) is essential to increasing our understanding of the early climate. Orbital study of geomorphic features at visible and thermal wavelengths has advanced considerably in recent years but would benefit further from more global coverage, particularly at the highest spatial resolutions. In-situ rover observations of the morphology of sedimentary features can be used to constrain their formation timescales and conditions, particularly when this information is synthesized with data from other sources. Identification of oceans in the northern hemisphere from putative shorelines, boulder deposits, and other features remains highly debated, and the implications for the early martian climate system are important. Detailed study of these features in combination with careful geomorphological and hydrologic modeling is required to make progress on this problem.

Spectral identification of surface aqueous minerals, both orbital and in-situ, and associated modeling must also be pursued to infer formation timescales and conditions. More information is also needed on the extent and temporal evolution of martian groundwater systems. This can be best accomplished through a combination of orbital identification of subsurface volatile and mineral deposits and better characterization (either orbital or in-situ) of regions where groundwater is implicated in the surface geomorphology and mineralogy. Finally, radioisotope dating of returned samples could provide vital constraints on the formation time of observed surface fluvial features and mineralogy; this should be regarded as an extremely high priority component of this Investigation.

Goal II, Investigation C2.2: Characterize the ancient climate via modeling and constrain key model boundary conditions. (Higher Priority)

Cross-Cutting: Goal I: A2, B1; Goal III: A1, A3

Several advances in climate modeling are still required to advance our understanding of early martian conditions. Better understanding of the radiative effects of various gases and gas combinations is needed, as are advances in understanding of the microphysics and radiative effects of clouds and aerosols under a range of conditions. The mesoscale and microscale physics of convection and precipitation under early martian conditions also requires further detailed investigation. Both of these topics would benefit from theoretical/numerical and potentially laboratory investigation. The global-scale interaction between atmospheric dynamics, the water cycle and the dust cycle under different topographic and atmospheric conditions needs further study, ideally via the hierarchical modeling approach that is now mainstream in Earth systems science. Finally, a diverse range of approaches are required to improve constraints on the ancient topography, solar evolution through time (both in terms of total flux and solar spectrum), and state of the magnetic field. Many of these constraints are of inherent interest from a planetary science standpoint, but they also have particular importance for long-term evolution of the Mars climate system.

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 water and other **volatile reservoirs.**
	A2. Document the geologic record preserved in **sediments and sedimentary deposits**.
	A3. Constrain the magnitude, nature, timing, and origin of **environmental transitions**.
	A4. Determine the nature and timing of **construction and modification of the crust.**
B. Determine the structure, composition, and dynamics of the **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 origin and geologic history of **Mars' moons** and implications for the evolution of Mars.	C1. Constrain the **origin of Mars' moons** based on their surface and interior characteristics.
	C2. Determine the material and **impactor flux** within the Mars neighborhood, throughout martian history, as recorded on Mars' moons.

Among the many scientifically compelling motivations for scientific investigation of Mars, study of the planet's interior and surface composition, structure, and geologic history is fundamental to understanding the solar system as a whole, as well as providing insight into the geologic evolution of terrestrial planets. Earth-like planets and environments are relatively rare in the history of the solar system, and are important natural laboratories to probe the factors that foster or inhibit life. The history of Mars has aspects similar to Earth's evolution, particularly in its early history, and may provide valuable constraints on its early history that are not preserved in the geologic record on Earth. In addition, Mars serves as a counter-example to Earth as there are many ways in which Mars has no terrestrial analog. Indeed, studies of Mars geology may contribute towards new types of comparative planetology investigations with the outer solar system, where 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. 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 (Goal I), and the study of the interior provides important clues about a wide range of topics, including the early Mars environment and sources of volatiles. Studies of martian geological landforms yield proxy records of past and present processes and the environment, including a record of climate and climate shifts (Goal II). Additionally, many geological investigations are foundational for human exploration (Goal IV), including hazard, safety, and trafficability assessments, and identification of in-situ resources.

Goal III encompasses the geoscience research that is foundational for addressing all MEPAG Objectives. Because of the interdisciplinary nature of geoscience research, most cross-cutting relationships between Goal III investigations are not explicitly identified in order to streamline the document; however, cross-cutting relationships to other MEPAG Goals are identified for each Investigation.

Prioritization

Multiple factors went into assigning relative priority designations, including the degree to which an investigation would be likely to *(a)* be uniquely game-changing for Mars science, *(b)* yield meaningful results pertaining to decadal-level questions, *(c)* provide time-critical information to foster on-going or planned mission objectives, or *(d)* increase measurement accuracy. Three priority levels were assigned (higher, medium, lower) to all Goal III tiers (Objectives, Sub-Objectives, and Investigations). Because it is recognized there is overlap and interdependability between sub-objectives and investigations within Goal III, no relative ranking is implied by the order in which they are listed. All Goal III investigations have significant scientific merit and are worthy of research as they factor into a broad understanding of terrestrial environments and solar system evolution. Nevertheless, those investigations that foster general characterization often were designated of lower relative priority. In some cases, a high science-value Investigation may be prioritized lower than another Investigation because its accomplishment is less likely within the decadal 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 than those that did not.

Goal III, Objective A: Document the geologic record preserved in the crust and investigate the processes that have created and modified that record. (Higher Priority)

Perhaps uniquely in the solar system, the martian crust preserves a long record of the diverse suite of ancient and modern processes that shaped it. These include differentiation and volcanism recording the evolution of the crust-mantle system, sedimentary processes recording changing climate and habitable environments over time, and modification of the surface by impact, wind, ice, water, and other processes. Many of these processes also acted upon the Earth, but much of that record has been lost due to plate tectonics and high erosion rates. Thus, this Objective has the potential to significantly improve our knowledge of the evolution of Earth and other Earth-like planets. Mars' crustal structure, composition, and landforms provide important constraints on a variety of processes critical to the evolution of habitable worlds, including: reconstructing past and present climates and environments; 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 the process and environmental conditions involved based on both present-day surface changes and observed landforms, structures and rock attributes (sometimes evolving, sometimes relict). Many of the Goal III Investigations are interrelated and could be addressed by common data sets and/or methodologies. For the purposes of Goal III, we define "crust," as the outermost solid shell of Mars (including bedrock, sediments and icy deposits) that is compositionally distinct from deeper layers.

Goal III, Sub-Objective A1: Identify and characterize past and present water and other volatile reservoirs. (Higher Priority)

Water, in all phases, has played and continues to play a critical role in shaping and transforming Mars, and water is one of the primary reasons for our sustained fascination with the red planet for both scientific and human exploration. Other volatiles like CO_2 are also major geological drivers on Mars, and thus are included in this Sub-Objective where their impact on the evolution of the crust is important. Understanding the past and present distribution and activity of liquid water and ices is critical for interpreting the geologic record, linking the record to climate/paleoclimate (Goal II), and characterizing the past and present habitability of the surface and sub-surface (Goal I). This Sub-Objective also provides critical information regarding resources needed for human exploration (Goal IV).

<u>Goal III, Investigation A1.1:</u> Determine the modern extent and volume of liquid water and hydrous minerals within the crust. (Higher Priority)

Cross-Cutting: Goal I: A2.1; Goal IV: C2.1

Understanding the present distribution of water on Mars, including adsorbed water, possible surface manifestations (e.g., RSL), and potential deep aquifers, is not only part of assessing the modern volatile inventory, but is also foundational information for interpreting water-related paleoclimate indicators in the past. Additionally, mineral-bound water is part of this Investigation, and necessitates determination of the composition and location of various hydrous minerals in the stratigraphic record. The volume of both liquid water and hydrous minerals is important for exploration and science concerns, as these could serve as important resources for human exploration (Goal IV), and understanding the distribution and chemistry of modern liquid water is critical for evaluating the modern habitability of the surface and subsurface of Mars (Goal I). An outstanding question is whether or not near-surface brines exist, which could be tested with landed surface-penetrating instruments, or surface imaging campaigns and coordinated environmental monitoring. The present distribution of liquid water on Mars can be characterized across many scale ranges, and investigated via thermal, visible and radar imaging, spectral and spectroscopy data, and/or seismic and other geophysical sounding. In situ or returned sample analyses (e.g., XRD, petrography) are particularly diagnostic of hydrous mineralogy and mineral abundances.

<u>Goal III, Investigation A1.2:</u> Identify the geologic evidence for the location, volume, and timing of ancient water reservoirs. (Higher Priority)

Cross-Cutting: Goal I: A2.1; Goal II: C2.1

Understanding the distribution of water and water ice in the past is intimately tied to characterizing the climate history and past local and planet-scale habitability. The presence of former surface and sub-surface water reservoirs (lakes, aquifers, oceans, ice sheets/glaciers, ground ice, etc.) can be deduced based on geomorphic attributes and mineralogical signatures. Geologic context determined from mapping and stratigraphic correlation provides insight into the nature, scale, relative sequence, and migration of these water reservoirs. Of particular importance is determination of the relative preponderance of ice versus liquid water at the surface over time, the surface coverage of these phases, and regional variations in their distribution. Linking relevant observations to climate models provides critical constraints on the coupled evolution of surface environments and the climate over time (Goal II). Returned sample analyses would also provide quantitative constraints on timing of water activity through geochronology of sediments and aqueous minerals. In addition, here and in other related investigations, returned sample analyses may be necessary for ultimate diagnosis of the origin of some hydrous minerals, as detailed analysis of properties like petrographic relationships via microscopy, isotopic and chemical compositions of individual minerals and fluid inclusions, etc., are challenging with in situ instrumentation.

Goal III, Investigation A1.3: Determine the subsurface structure and age of the Polar Layered Deposits (PLD) and identify links to climate. (Medium Priority)

Cross-Cutting: Goal II: B1, C1.3

One of the key records of paleoclimate fluctuations is in the PLD and cap, but the details preserved there have yet to be well characterized and understood. The polar cap stratigraphy at the largest scales has been identified by radar studies and suggests a complex history of accumulation and erosion, but the origin of outcrop-scale stratigraphy (layer formation, stability, origin of entrained salts and sediments) is still poorly understood. It is also unclear whether or not there are any stratigraphic correlations between the caps reflecting global conditions. Finally, the age of both caps is also a major outstanding question. All of these aspects of the PLD must be resolved in order to attempt to link their stratigraphic record to recent climate change. A range of techniques can be applied to this Investigation, such as active sub-surface radar or seismic sounding, neutron and other spectroscopies, radar, thermal and visible imaging, and subsurface ice collection and characterization. Acquisition of higher resolution radar data would facilitate finer-detailed discrimination of the polar cap architecture. Ultimately, a landed investigation is likely to be required to constrain the fine scale stratigraphy and history of the PLD, either through rover investigations of exposed strata or a landed drilling platform. Such a mission could be equipped with instruments to determine key ice properties (e.g., stable isotopes as well as other physical, electrical, and chemical properties of ices, sediments, and trapped gases) and potentially methods for dating entrained sediments or trapped gases. Note there is tremendous synthesis with (and further detail on) this topic within Goal II, Sub-Objective B1. Building upon Investigation A1.5 in this Goal, studying current volatile-driven processes can aid in identifying past expressions of those processes in the polar subsurface and their climatic impact.

Goal III, Investigation A1.4: Determine how the vertical and lateral distribution of surface ice and ground ice has changed over time. (Medium Priority)

Cross-Cutting: Goal I: A2.1; Goal II: B1; Goal IV: C2.1

Evaluating the temporal evolution of the volatile budget requires documentation of the three-dimensional spatial distribution and vertical structure of water and CO_2 ice content in the upper crust and at the surface (including frosts). In addition to the polar ice caps, recent radar and visible observations have demonstrated the presence of abundant mid-latitude ground water ice, an important potential resource for human exploration (Goal IV) and a possible recent habitat (Goal I) that should be characterized in terms of refining the location, water volume, composition (water versus other ice compositions; water to sediment ratio), history of emplacement and modification, and accessibility. Linking geomorphic expression of water and CO_2 ice-modified terrain to ice volume and temporal constraints is also critical for characterizing the distribution of ice geographically, and how that changed over martian history. A range of techniques can be applied to this Investigation, such as active sub-surface radar or seismic sounding, neutron and other spectroscopies, radar, subsurface ice properties (e.g., stratigraphic records of ice stable isotopes as well as other physical, electrical, and chemical properties), as well as thermal, infrared and visible imaging. Monitoring of modern ice-related exposures and landforms with high resolution images for change detection and process characterization also provides information relevant to this investigation.

Goal III, Investigation A1.5: Determine the role of volatiles in modern dynamic surface processes, correlate with records of recent climate change, and link to past processes and landforms. (Medium Priority)

Cross-Cutting: Goal II: A2, C1.3

Many sites of ongoing large- and small-scale changes have been identified on the rocky and icy surfaces of Mars that potentially involve volatile exchange (e.g., CO_2, methane, water, etc.). Examples of possible or likely volatile-driven active surface modification include, but are not limited to, mass-wasting, gullies, Swiss-cheese terrain, polar 'spiders', RSL, and changes observed in the modern polar cap (e.g., pit enlargement, avalanches, etc.). However, knowledge of how volatiles and dust exchange between surface, sub-surface, and atmospheric reservoirs is not yet sufficient to explain the components and mechanisms involved, nor to extrapolate their effect on recent climate change and relationship to the paleoclimate record. Fundamental to advancing scientific understanding from this investigation is linking active surface processes to their expression in the rock and ice records to interpret the geologic fingerprints of climate changes.

Qualitative, quantitative, and compositional documentation of on-going landscape and deposit evolution from orbital and/or landed missions is needed to evaluate formation mechanisms, characterize the nature of surface-atmosphere interactions, and constrain volatile and/or sediment fluxes. Additional change detection monitoring from orbital and surface instruments will yield improved constraints on the driving environmental conditions. Measuring the rate of activity and the variations in these rates between seasons or Mars years is also important for extrapolating the effect of these surface changes over longer timescales and necessitates dedicated observational campaigns. This Investigation would benefit from focused, landed investigations to particular active sites of interest to enable hypothesis testing of formation mechanisms with data that is not achievable from orbit. In situ observations would provide greater temporal coverage of landform modification process (including the possibility of continuous monitoring), and would enable measurements of surface and subsurface environmental conditions. This Investigation would also benefit from laboratory simulations or measurements, or modelling, to interrogate volatile-related processes and their surface manifestations.

Goal III, Sub-Objective A2: Document the geologic record preserved in sediments and sedimentary deposits. (Higher Priority)

Outside of Earth, Mars may be unique in the solar system for the extensive role of sedimentary processes that have operated on the surface. The diversity of processes (e.g., aeolian, glacial/periglacial, fluvial, lacustrine, and other processes) that have formed that record, coupled with chemical and mechanical erosion, attest to a complicated geologic history. The sedimentary record provides a unique documentation of the evolution of these geologic processes, climate, and habitable environments over time. Deciphering the depositional environment and post-depositional alteration is paramount to addressing decadal-level science questions, and requires interdisciplinary investigation that is augmented/optimized by in situ observation or sample return as many of the key lines of evidence are at the outcrop, hand sample or thin section scale.

Goal III, Investigation A2.1: Constrain the location, volume, timing, and duration of past hydrologic cycles that contributed to the sedimentary and geomorphic record. (Higher Priority)

Cross-Cutting: Goal II: C2.1

Within the solar system, Mars is an extremely rare geologic system that featured liquid water at the surface. Details on pathways, processes, magnitude and timing of recent and ancient cycling of water on Mars, including exchange with the cryosphere and possible deep aquifers, are needed to characterize water reservoir distribution (Goal III.A1) and paleoclimate implications (Goal II). The history of aqueous processes is recorded in erosional landforms, sediments, and sedimentary rocks formed in and near fluvial, lacustrine, glacial/periglacial or other depositional regimes. Also pertinent to this Investigation is the identification (type and location) and characterization of phase-changes (solid, liquid or vapor) over time. Reconstructing the martian hydrologic cycle involves multiple sub-tasks, such as determining the role and phase of water in sediment mobilization processes, and estimating the scale and magnitude of aqueous events at multiple locations and throughout history. Coupled high resolution images and topographic data, compositional information, and near-surface radar imaging all aid in identifying aqueous process and magnitude. Increased coverage of topographic data at scales <50 m/pix (ideally <10 m/pix) would be particularly informative for constraining the scale and duration of aqueous events, as such high resolution data presently only exists for select areas. As noted in Investigation A1.2, returned sample analyses would provide significant additional constraints on the specific timing and chemistry of aqueous processes.

<u>Goal III, Investigation A2.2:</u> Constrain the location, composition and timing of diagenesis of sedimentary deposits and other types of subsurface alteration. (Higher priority)

Cross-Cutting: Goal I: A1.2, A2.1, B2.4

On Earth, lithification of sedimentary rocks is enabled by abundant water interactions, but the mechanisms of these diagenetic processes on Mars and how they changed over time is poorly understood. While diagenesis is a critical step in preservation of the sedimentary record on Mars, diagenetic fluids and processes acting on sedimentary rocks can negatively affect their organic and biosignature preservation potential as well as our ability to interpret past environments from their mineralogy and chemistry. However, diagenetic processes and related groundwater systems can also produce long-lived habitable subsurface environments (e.g., low-T aquifers or hydrothermal systems). Improved detection of environmental indicator minerals through spectroscopy and high-resolution color imaging, especially in association with geomorphic expressions of water processes or reservoirs, would help constrain past fluid migration, and constrain lithification and alteration environments. Ultimately, a detailed understanding of diagenetic processes via macroscopic and microscopic diagenetic relationships, textures, and chemistries will require microscopic studies of rock samples both via in situ analysis and sample return.

<u>Goal III, Investigation A2.3:</u> Identify the intervals of the sedimentary record conducive to habitability and biosignature preservation. (Higher Priority)

Cross-Cutting: Goal I: A1, A2, A3; Goal II: B1, C2

Sedimentary rocks are the most likely materials to preserve traces of prebiotic compounds and evidence of life, especially those deposited in lacustrine, fluvial, or hydrothermal environments. Therefore, assessment of their depositional environment and diagenetic history is important for informing the search for signs of life. This investigation thus provides critical support for Mars sample return, both for formulation of a returned sample selection strategy and for placing the results in a global Mars context. Critical to this investigation is high-resolution imaging across a range of scales (orbital to outcrop to grain-scale), ideally in color and stereo, to characterize the three-dimensional stratigraphic architecture, sedimentary structures and textures, and grain size distribution of sedimentary deposits. These imaging datasets should then be correlated with geochemistry, mineralogy, and organic content. Geologic mapping, based on remote sensing data, underpins this investigation in locating in time and space where life, if present, could exist and leave a record. Several complimentary Goal III investigations (e.g., A2.5, A4.5, etc.) aid the objective of identifying these sedimentological facies and depositional environments, but importantly many are not required to successfully advance knowledge in this Investigation. Insights into biosignature preservation may also be gleaned from relevant/appropriate terrestrial analogs or laboratory simulations.

Goal III, Investigation A2.4: Determine the sources and fluxes of modern aeolian sediments. (Lower priority)

Cross-Cutting: Goal II: A1.1, A2; Goal IV: B3

One of the most active agents of surface modification on Mars today is wind, which erodes, transports, and deposits sand and dust. Identification of present or recent aeolian sediment fluxes and transport pathways enables linkage between global and regional atmospheric circulation and aeolian bedforms and evidence of erosion. Linking modern sediment sources, transport pathways, and fluxes to the sedimentary rock record provides key insight into sediment cycles and the identification of aeolian sedimentary rocks from past eras. Aeolian sediments record a combination of globally averaged and locally derived, fine-grained sediments and weathering products. The geologic sources of aeolian sediments on Mars today are poorly constrained; however future compositional characterization coupled with geomorphic evidence of transport directions could be used to identify likely sediment sources. To constrain sediment fluxes and transport pathways requires high-resolution change detection monitoring of active sediment movement, including the migration and evolution of aeolian bedforms, and local albedo changes presumably related to dust lofting/settling.

Goal III, Investigation A2.5: Determine the origin and timing of dust genesis, lofting mechanisms, and circulation pathways. (Lower priority)

Cross-Cutting: Goal II: A1.2, A2.1; Goal IV: B3

The origin of ubiquitous martian dust, when the modern dust inventory was first created, and whether or not dust is still forming today are all open questions, and represent a major knowledge gap in our understanding of the climatic and geologic influence through time of this important component of the martian atmosphere. Compositional and morphological studies of dust samples (in situ or returned sample analyses) and searches for the spectral or morphological signatures of dust in the sedimentary record are needed to resolve this knowledge gap. Current knowledge of the processes that control the lifting of dust from the surface and into the atmosphere is also insufficient, but is critical for input into climate models. The most fundamental processes for dust lifting are thought to be the shear stress exerted by the wind onto a dusty surface, and ejection due to saltation of sand-sized particles. This model can be tested via in situ observations of saltation and lifting coupled to simultaneous meteorology measurements. Furthermore, rapid pressure changes associated with dust devils and electrostatic forces also may be important in dust mobilization. In the south polar region, dust injection by seasonal CO_2 jets may also be significant. Local and global-scale monitoring of dust transport via repeat imaging as well as in situ measurements of saltation, lifting and detailed meteorology are needed to address these questions.

Goal III, Sub-Objective A3: Constrain the magnitude, nature, timing, and origin of ancient environmental transitions. (Higher priority)

Evidence for ancient climate change on Mars is based on a variety of observations that suggest changing surface environments, including ancient valley networks, heavily eroded craters, the presence of various minerals in the stratigraphic record, and banded sedimentary deposits. Previous landed and orbital missions have shown significant diversity in the nature of ancient aqueous environments. While additional work is needed to characterize these environments and establish the full range of environments that may have persisted on ancient Mars, the most critical outstanding knowledge gaps surround their distribution, timing, and duration, and through these aspects their links to global processes like climate. Tighter constraints on the magnitude, timing, and nature of past planet-wide climate changes are a key input into climate models and our broader understanding of habitability through time.

Goal III, Investigation A3.1: Link geologic evidence for local environmental transitions to global-scale planetary evolution. (Higher priority)

Cross-Cutting: Goal I: A2.5; Goal II: C2

Rover investigations and high-resolution orbital imaging and spectroscopy have provided evidence for a diverse array of local surface environments on ancient Mars over time, but the relationship between these disparate observations and the evolution of Mars as a planet is not always clear. In some cases, environmental transitions may be related to global-scale processes like changes in climate or atmospheric properties (e.g., pressure, composition) as well as volcanism and impacts, through their effects on surface aridity and temperature, global-scale surface and sub-surface hydrology, and surface chemistry. In other cases, they may only reflect local variability in parameters like water/sediment sources, fluid chemistry, and aeolian/impact/volcanic processes. More work is needed to understand how representative geologic processes and past environments at specific landing sites are of Mars during the relevant geologic epoch and how that moment in time relates to the broader evolution of the planet. Color imaging and spectroscopic datasets at intermediate resolutions (~5-20 m/pix) would facilitate detailed mapping of key geologic, geomorphic, and mineralogic environmental indicators, and landed investigations at sites with clear regional/global geologic context to provide new insights into this critical problem.

Goal III, Investigation A3.2: Determine the relative and absolute age, durations, and periodicity of ancient environmental transitions. (Higher priority)

Cross-Cutting: Goal II: B1

Global-scale observations of geomorphology and mineralogy suggest a general decline in water activity and atmospheric pressure over time on Mars, but more detailed local investigations from orbit and landed missions suggest that the nature of the decline was much more complicated. For example, while the majority of well-connected valley networks occur on late Noachian/early Hesperian surfaces, smaller drainages and groundwater may have fed persistent lakes (e.g., Gale crater) or playas (e.g., Meridiani Planum) in the Hesperian, and some Amazonian valley networks and deltas have been identified. Thus, the timing, duration, and periodicity of climate cycles or perturbations that may have produced these wet epochs, and their regional versus global influence, are poorly constrained. The nature of the climate and surface environment prior to the late Noachian is also unclear. Results of this Investigation bear directly on identifying spatial and temporal habitability niches (e.g., relevant to Goal III: A2.3).

Synthesis of knowledge gleaned from multiple investigations on environmental conditions, age and timescales is paramount to addressing this investigation. Knowledge advances are possible at individual locations (e.g., detailed outcrop-scale analysis from ground and orbital observations), as well as via regional or global studies. This Investigation builds from information gleaned from other investigations in Sub-Objective A3. Age-dated sample(s) from in situ and/or returned sample isotopic analysis are required/needed for absolute age control. This Investigation also can be addressed via integrated chronological information from superposition relationships and geologic mapping to determine stratigraphic correlations, modelling landform or deposit formation timescales and crater-age dating of geologic units.

Goal III, Investigation A3.3: Document the nature and diversity of ancient environments and their implications for surface temperature, geochemistry, and aridity. (Medium Priority)

Cross-Cutting: Goal II: B1

Past landed and orbital missions have made significant progress on this Investigation, and have identified a diverse array of geochemical and physical attributes of ancient aqueous environments at specific locations on Mars. However, the detailed properties of these environments, their extent, links to surface versus subsurface processes, links to local versus global processes, and their full dynamic range require additional investigation. Through identification of paleoclimate indicators in the geologic record, there is the potential to recognize variations in the martian environment over time, especially to distinguish whether temporal variation was persistent, transient, or episodic. Understanding the rock-formational environment, especially the timing and nature of surface water and ice, provides valuable insight into environmental evolution. Pertinent to paleoclimate studies is determining the evolution of the geochemical setting and surface conditions (e.g., temperature, humidity, atmospheric pressure). Mapping environmental gradients (e.g., pH, H_2O activity, energy, nutrients, key elements, etc.) is also relevant to assessing habitable periods and locations. These parameters can be constrained based on compositional data in concert with geologic context.

Goal III, Investigation A3.4: Determine the history and fate of sulfur and carbon throughout the Mars system. (Medium Priority)

Cross-Cutting: Goal I: B1

In addition to serving as basic building blocks for life, sulfur and carbon are important geologic records of the chemistry and redox conditions of crustal fluids and the atmosphere, volatile sources, and weathering processes. Carbon is also a critical record of atmospheric loss, and the carbon content of the martian interior is poorly constrained. Thus, sulfur- and carbon-bearing sedimentary rocks are critical targets for in situ investigations and high precision isotopic analyses, most likely through sample return. However, the extent to which carbon and sulfur cycling affected the chemistry and stability of early Mars surface environments is particularly unclear and would benefit from additional information on the distribution of sulfur- and carbon-bearing minerals, from higher spatial or spectral resolution orbital spectroscopy and in situ analyses.

Goal III, Sub-Objective A4: Determine the nature and timing of construction and modification of the crust. (Medium Priority)

The martian crust contains a record of processes that shaped and modified it, and this Sub-Objective addresses the critical issue of the relative and absolute timing of important geologic events on Mars as well as two major processes that contributed to construction and modification of the crust that are not covered in the Sub-Objectives above – impacts and igneous processes.

Goal III, Investigation A4.1: Determine the absolute and relative ages of geologic units and events through martian history. (Higher priority)

Cross-Cutting: Goal II: B1.3, B2.2, C2.1

Temporal constraints are critical to reconstructing the martian geologic history, and comparing Mars to Earth's history. The evolution of the surface and 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. Relative timing of some geologic terrain units can be estimated from crater size-frequency modeling (Investigation A4.1) and superposition relationships. Thus, this Investigation is founded on geologic mapping for relative ages (Investigation A4.6). Absolute ages could be approached with in situ and/or returned sample isotopic analysis.

Goal III, Investigation A4.2: Constrain the effect of impact processes on the martian crust and determine the martian crater production rate now and in the past. (Medium priority)

Cross-Cutting: Goal II: B2.2

Impacts are one of the global processes shaping the crust and surface of Mars, and they are a crucial tool in estimating the ages of geologic units. Impact events influence environmental conditions—both in the subsurface with thermal effects that can influence volatile reservoirs and above ground with atmospheric injection of material—with implications for habitability and biosignature preservation as well as the martian volatile budget. A detailed understanding of impact events on Mars' crust, structure, topography and thermal history, is a prerequisite for any broad understanding of the geometry and history of the crust and lithosphere. Significant work has been conducted to document global crater populations and their morphologies, with outstanding questions on crater degradation processes and rates. This Investigation will require studies of both individual craters and crater populations within various geologic terrains to assess morphologic characteristics as they relate to crater degradation over time. Geologic crater mapping using global topographic data combined with high-resolution images and remote sensing data aids in linking crater attributes to impact effects (e.g., fluidized ejecta, shocked minerals, etc.), including surface modification that may be caused by the impact event but occurs well after (days to years) crater formation. Subsurface radar imaging would be informative for identifying how buried craters manifest on the surface (e.g., correlations with topographic or chemical signatures), as well as characterizing the total impact crater inventory in three dimensions.

Studies of this nature will also inform our knowledge of the martian crater production rate, which is needed for accurate age determination. Although the impact flux is known to have varied over time, determination of crater impact rates is complicated by the modification of crater morphology due to extensive erosional and depositional cycles, processes that are largely absent on airless worlds, and these processes are spatially variable. Thus, delineating craters from different eras through geologic mapping, folding in information about crater evolutionary processes and local stratigraphy, is necessary to refine the martian crater production rate over time. Study of modern impact events are also part of this investigation to measure the present-day impact rate, as well as understanding crater morphology, degradation and environmental effects; both orbital monitoring (e.g., change detection imaging, thermal signatures, etc.) and subsurface detection (e.g., seismometers) are useful in identifying and characterizing present-day impact events.

Goal III, Investigation A4.3: Link the petrogenesis of martian meteorites and returned samples to the geologic evolution of the planet. (Medium Priority)

Cross-Cutting: Goal II: B3.2, C1.1

Meteorites and returned samples offer unprecedented opportunities to investigate in detail the origin and alteration history (with absolute ages) of martian sediments, regolith, and bedrock, placing important constraints on nearly every aspect of Mars history. Meteorites have provided key insights into the accretion, differentiation, and petrologic evolution of Mars through igneous samples and regolith formation of a few valuable samples, and new analytical techniques applied to future samples will continue to make valuable contributions. However, one of the challenges of meteorite studies is that the current sample collection does not appear to be representative of typical martian crust, either in terms of igneous geochemistry or lithology (e.g., given the wide distribution of sedimentary rocks at the martian surface). Thus, Mars sample return would provide a new diverse suite of carefully curated igneous, sedimentary, regolith, and other specimens with the added benefit of clear and well-understood geologic contexts. For example, microscopy and volumetric imaging techniques applied to returned samples can provide fundamental advances in mineralogy/petrology and thus the origin and evolution of the rock or sediment. Examination of trapped gases or fluid inclusions, if present, can reveal information on the rock formation conditions (e.g., temperature, salinity, pressure, depth of trapping) and/or paleo-atmospheric composition via techniques such as microscopy, spectroscopy, and gas chromatography, and these analytical techniques are more easily done in Earth laboratories than using remote rover/lander instruments. More development of scientific strategies for in situ characterization and selection of these samples as well as curation and later analyses are needed to maximize return from this critical effort.

Goal III, Investigation A4.4: Constrain the petrology/petrogenesis of igneous rocks over time. (Lower Priority)

Cross-Cutting: Goal II: C1.3

The martian crust was formed initially through igneous processes, and igneous rocks record the evolution of the crust/mantle system over time. While the crust is dominantly basaltic in composition, recent orbital and rover studies have shown evidence for significant local variability in magmatic evolution; however, the origin and extent of evolved materials is poorly constrained. Understanding primary igneous lithologies is also key to interpreting alteration processes that have produced secondary minerals. Further, there is evidence for a change in either mantle melting conditions or mantle chemistry producing magmas with different bulk chemistry through time, but additional data is needed to determine the nature and timing of these changes. Petrologic characterization of Mars requires orbital and surface characterization of bulk geochemistry and bulk mineralogy, as well as detailed characterization of physical rock properties and mineral relationship, trace elements, and isotopic analysis from in situ or laboratory sample analysis through sample return.

Goal III, Investigation A4.5: Determine the surface manifestation of volcanic processes through time and their implications for surface conditions. (Lower Priority)

Cross-Cutting: Goal II: C1.2, C1.3

Volcanic processes are major contributors to construction and modification of the crust over time, and are an important contributor to juvenile and meteoric volatiles. While deposits from effusive eruptions have been documented, the volume and distribution of deposits from explosive eruptions and their causes are much less well understood. Explosive volcanic processes may have dominated early in Mars history, and may have been a major contributor to the martian sedimentary cycle and/or climate conditions (e.g., atmospherically-injected volcanic ash reducing surface temperature and altering circulation patterns). Explosive volcanic eruptions can be triggered by interactions between magma and water or ice, which each produce distinctive deposits that can provide a record of past surface conditions and climates (e.g., wet versus icy). Orbital and surface measurements, across a range of resolutions, of composition (primary mineralogy/petrology as well as syn-eruptive and hydrothermal alteration), morphology (from landforms to grain-scale textures), and other aspects are needed to better constrain the contribution of explosive versus effusive volcanism to the martian crust. Volcanic samples are high priority for sample return for their ability to constrain timing of processes on Mars, and laboratory analysis of these samples would also provide the opportunity to investigate the details of one or more volcanic deposits to constrain the properties listed above.

Goal III, Investigation A4.6: Develop a planet-wide model of Mars evolution through global and regional mapping efforts. (Lower priority)

Cross-Cutting: Goal I: A1.5; Goal IV: A3, C2.2, D1.1

Synthesizing geological activity as a function of time involves determining the relative role and sequence of different terrain-building and surface modification processes (volcanism, tectonism, impact cratering, sedimentation, erosion) across the globe. 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. Geologic mapping is greatly enhanced from integration of orbital and rover/lander observations, where available, because diagnostic information on formation process or stratigraphic context can be at outcrop to rock-specimen scale. Additionally, surface observations can be especially informative for geologic mapping because they can be acquired at higher resolution, with coordinated instrument measurements, with multiple viewing geometries, and/or with outcrop/sample preparation to enhance instrument measurements. Thus, a greater number and diversity of surface observations is desired.

Goal III, Objective B: Determine the structure, composition, and dynamics of the interior and how it has evolved. (Medium Priority)

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.

Goal III, Sub-Objective B1: Identify and evaluate manifestations of crust-mantle interactions. (Medium Priority)

Goal III, Investigation B1.1: Determine the types, nature, abundance, and interaction of volatiles in the mantle and crust, and establish links to changes in climate and volcanism over time. (Higher priority)

Cross-Cutting: Goal IV: E1

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.

Goal III, Investigation B1.2: Seek evidence of plate tectonics-style activity and metamorphic activity, and measure modern tectonic activity. (Medium Priority)

Cross-Cutting: Goal IV: E2

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 true, 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 environment 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.

Recent and ongoing detections of marsquakes by the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport mission (InSight) will make a major contribution to this Investigation by constraining the present level of seismicity on Mars via a single, well-coupled seismic station. The next step would be more accurate localization of marsquakes in space and time to fully understand the distribution and intensity of current tectonic activity. This could 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.

Goal III, Sub-Objective B2: Quantitatively constrain the age and processes of accretion, differentiation, and thermal evolution of Mars. (Medium Priority)

Goal III, Investigation B2.1: Characterize the structure and dynamics of the interior. (Higher priority)

Cross-Cutting: Goal IV: E1.1, E1.2

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), gravity data, precision tracking for rotational dynamics, and electromagnetic sounding. Given the paucity of data on the martian interior, significant progress in this Investigation will be made with InSight, which aims to obtain key information on interior structure and processes using single-station seismic, heat flow, and precision tracking data. Beyond InSight, more accurate localization of seismic activity outside of this single region and validation of models and assumptions used to interpret the data is necessary to fully address this Investigation, for example, using at least four stations operating simultaneously for a full Mars year. Another valuable next step in this investigation would be higher resolution gravity data, such as those enabled by mission architectures similar to GRACE at Earth or GRAIL at the Moon.

Goal III, Investigation B2.2: Measure the thermal state and heat flow of the martian interior. (Medium Priority)

Cross-Cutting: Goal IV: E2.4

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. Characterizing the martian thermal state has important implications for the thermal history of terrestrial planets in general. This Investigation would require measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships. Such 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. To address this Investigation, follow-up missions from InSight may be warranted due to technical instrument deployment challenges.

Goal III, Investigation B2.3: Determine the origin and history of the magnetic field. (Medium Priority)

Cross-Cutting: Goal IV: E1

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. Recent observations have shown a stronger than expected magnetic field at the surface which exhibits small scale structure that warrants better characterization and understanding links to geodynamo origin and evolution. 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.

Goal III, Objective C: Determine the origin and geologic history of Mars' moons and implications for the evolution of Mars. (Lower Priority)

Much like Earth's Moon, the moons of Mars, Phobos and Deimos, likely preserve an independent record of many key events in the Mars system that will provide key insights into the formation and evolution of Mars itself. The moons may help to constrain early accretion and/or impact processes, as well as the impact flux over time, and may even preserve martian materials acquired during accretion or later impacts. The moons may also serve as an important physical and tactical resource for future human exploration (Goal IV).

Goal III, Sub-Objective C1: Constrain the origin of Mars' moons based on their surface and interior characteristics. (Medium Priority)

The martian moons, Phobos and Deimos, are generally accepted to be bodies with an ancient origin and to have spent most of their history in orbit about Mars. Three main origin hypotheses have been proposed for the Mars moons – the capture model (formation outside the Mars system), the co-accretion model (formation along with Mars), and the large impact model (later formation in the Mars system). Determining the origin of these moons would provide useful information about the early formation of Mars that cannot be determined through other means, and would provide important constraints on the formation of moons in the solar system more generally. Critically, because the moons may have independent origins, completing these Sub-Objectives requires investigation of both moons.

Goal III, Investigation C1.1: Determine the thermal, physical, and compositional properties of rock and regolith on the moons. (Medium priority)

Cross-Cutting: Goal IV: E1, E2.1

Determination of the compositions of Mars' moons is likely to provide the most rigorous test of various origin theories (especially when coupled with morphological data and interpreted within a geologic history, see Investigation C1.2). 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. This investigation would benefit from a surface sample to identify mineralogy and petrology, as well as the role of space weathering. Better constraints on the thermophysical properties of the regolith will also help to constrain grain sizes, surface roughness, porosity, and composition, all of which are critical both for interpreting the history of the regolith and as input for studies of the resource potential and strategic use of the moons for human exploration.

Goal III, Investigation C1.2: Interpret the geologic history of the moons, by identification of geologic units and the relationship(s) between them. (Medium Priority)

Cross-Cutting: Goal IV: E1

Although many observations exist of these moons, limited spectral and spatial resolution and low spectral signal-to-noise ratios have led to disagreement about what these observations imply about the moons' origin(s). For example, Phobos exhibits spectral heterogeneity, but the cause of the variability, the relationship between various spectral units, and whether or not pristine moon material is preserved at the surface are all still poorly understood. Better information on the geologic diversity of the moons would be informative as a discriminator between origin hypotheses, and in particular, more information is needed on the geologic context of compositional data. 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, understanding the geologic history of these moons is a necessary precursor to full interpretation of existing compositional data and other observations, especially with regards to determining the moons' origin(s). This investigation also includes characterizing modern surface processes on the moons. 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, landform investigations, stratigraphic ordering, and crater age dating.

<u>Goal III, Investigation C1.3:</u> Characterize the interior structure of the moons to determine the reason for their bulk density and the source of density variations within the moon (e.g., micro- versus macroporosity). (Lower priority)

Models of the orbits of Mars' moons shows that collision between the two moons was likely, on timescales shorter than the apparent ages of the moons. Thus, both the interior structure and the orbits of these moons may not be strict representatives of their original state, which creates difficulties in interpreting them 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 bulk density and density variations within each moon may provide insight into formation conditions and source materials, including if the moon had originally been monolithic and/or contain(ed) volatile reservoirs. This information could, for example, be determined from subsurface radar (of sufficient penetration depth and resolution) or high-resolution gravity maps.

Goal III, Sub-Objective C2: Determine the material and impactor flux within the Mars neighborhood, throughout martian history, as recorded on Mars' moons. (Lower priority)

<u>Goal III, Investigation C2.1:</u> Understand the flux of impactors in the martian system, as observed outside the martian atmosphere. (Lower Priority)

Cross-Cutting: Goal IV: A2.1

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. At present, 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. Of greatest value would be a global inventory of craters down to 100-m diameter, so as to *(1)* normalize out any hemispherical asymmetries (e.g., due the moons being tidally locked or leading versus trailing hemispheres), and *(2)* identify underrepresented crater-populations (due to downslope movement of material preferentially erasing smaller craters).

Goal III, Investigation C2.2: Measure the character and rate of material exchange between Mars and the two moons. (Lower priority)

Cross-Cutting: Goal IV: A2.1

As noted above, material may have been exchanged (and may continue to be exchanged) between the martian 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.

GOAL IV: PREPARE FOR HUMAN EXPLORATION

Objectives	Sub-Objectives
A. Obtain knowledge of Mars sufficient to design and implement human landing at the designated human landing site with acceptable cost, risk and performance.	A1. Determine the aspects of the atmospheric state that affect orbital capture and EDL for human scale missions to Mars.
	A2. Characterize the orbital debris environment around Mars with regard to future human exploration infrastructure.
	A3. Assess landing-site characteristics and environment related to safe landing of human-scale landers.
B. Obtain knowledge of Mars sufficient to design and implement human surface exploration and EVA on Mars with acceptable cost, risk and performance.	B1. Assess risks to crew health & performance by: (1) characterizing in detail the ionizing radiation environment at the martian surface & (2) determining the possible toxic effects of martian dust on humans.
	B2. Characterize the surface particulates that could affect engineering performance and lifetime of hardware and infrastructure.
	B3. Assess the climatological risk of dust storm activity in the human exploration zone at least one year in advance of landing & operations.
	B4. Assess landing-site characteristics and environment related to safe operations and trafficability within the possible area to be accessed by elements of a human mission.
C. Obtain knowledge of Mars sufficient to design and implement In Situ Resource Utilization of atmosphere and/or water on Mars with acceptable cost, risk and performance.	C1. Understand the resilience of atmospheric In Situ Resource Utilization processing systems to variations in martian near surface environmental conditions.
	C2. Characterize potentially extractable water resources to support ISRU for long-term human needs.
D. Obtain knowledge of Mars sufficient to design and implement biological contamination and planetary protection protocols to enable human exploration of Mars with acceptable cost, risk and performance.	D1. Determine the martian environmental niches that meet the definition of "Special Region" at the human landing site and inside of the exploration zone.
	D2. Determine if the martian environments to be contacted by humans are free, to within acceptable risk standards, of biohazards that could adversely affect crew members who become directly exposed.
	D3. Determine if martian materials or humans exposed to the martian environment can be certified free, within acceptable risk standards, of biohazards that might have adverse effects on the terrestrial environment and species if returned to Earth.
	D4. Determine the astrobiological baseline of the human landing site prior to human arrival.
	D5. Determine the survivability of terrestrial organisms exposed to martian surface conditions to better characterize the risks of forward contamination to the martian environment.
E. 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.	E1. Understand the geological, compositional, and geophysical properties of Phobos or Deimos sufficient to establish specific scientfic objectives, operations planning, and any potentially available resources.
	E2. Understand the conditions at the surface and in 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.

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" and/or efficiencies achieved 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 continue to 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 considered by the Precursor Strategy Analysis Group (P-SAG, 2012), who proposed the set of investigations that flowed into the 2012 version of the MEPAG Goals Document.

The topic of planetary protection and human exploration continues to be subject to changes and refinements in thinking. We anticipate that this topic will need frequent updating for the forseeable future. The most recent reports by the 2019 Planetary Protection Independent Review Board (PPIRB 2019) and the 2018 National Academies Review and Assessment of Planetary Protection Policy Development Processes (P3D Review) reflects the idea that human exploration will be conducted within an "exploration zone" which would contain human activities and might be subject to a different planetary protection policy than one for missions to other parts of the planet. However, that is currently not officially adopted in any NASA policy.

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/or possibly on nearby celestial objects such as the Moon and asteroids.

Prioritization within Objectives

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.

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. Over the past decade, NASA has continued to study and refine human Mars architecture concepts. In addition, several architectures independent from NASA have been proposed that have common elements as well as substantial differences from the NASA plans. The objectives detailed below are intended to be responsive to all currently proposed architectures but cannot be prescriptive for any individual architecture.

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. "Evolvable Mars Campaign 2016 – A Campaign Perspective," (Goodliff 2016), outlined the long-term, flexible and sustainable deep space exploration architecture that was intended to fulfill the principles in "Pioneering Space." The primary differences between DRA 5.0 and more recent concepts are: reduced lander size to mitigate crew landing risks, more attention to crew health and performance and planetary protection strategies, an emphasis on reusable mission elements, and an interest in leveraging Artemis lunar program assets for Mars (NASA's Strategic Plan for Human Exploration 2019).

Sub-Objective Prioritization

In setting the priorities for sub-objectives in Goal IV, the need for precursor data was considered along with the P-SAG priorities. Sub-objectives needed earlier are given higher priority than those needed later. This revision does not include prioritization at the investigation level. Across this document we did not find strong differences in priorities at the investigation level – therefore the sub-objective prioritization should be applied to all investigations within each sub-objective.

P-SAG (2012) based its priorities on the ability of each gap-filling activity (GFA) to address the issues related to increasing safety, decreasing cost, and increasing the performance of human missions to Mars. The priority levels, used within the P-SAG and which we have adopted in this document, 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

Goal IV, Objective A: Obtain knowledge of Mars sufficient to design and implement human landing at the designated human landing site with acceptable cost, risk and performance.

Goal IV, Sub-Objective A1: Determine the aspects of the atmospheric state that affect orbital capture and EDL for human scale missions to Mars. (High Priority)

The atmospheric precursor data would provide a combination of mission-enabling observations and improvements in knowledge needed to reduce required vehicle margins. Specifically, these data would reduce vehicle margins by improving knowledge associated with aerocapture and aerobraking, vehicle margins are elevated to reduce risk to mission and crew. 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 vehicle margins.

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 technique, replacing parachutes, to deliver large payloads (>2t) to the surface. Although the use of propulsion guards against atmospheric unknowns, the atmospheric properties in the current database have large error bars and thus require significant fuel reserves to lower overall risk.

However, while it was passively demonstrated on MSL, a new approach is to use pressure and density measurements taken during entry and feed them directly to the guidance algorithms during entry thus reducing atmosphere dispersions. A mission that demonstrates this capability would be of more value to aerocapture and EDL than collecting more data to improve model results.

Likewise, architecture investments in surface and/or orbiting instruments may be more productive towards enabling precision landing than improved atmosphere modeling.

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 landing systems for Mars. The observations are designed to both directly support engineering studies and to validate atmospheric numerical models. Existing recent observations fulfill some of the investigation requirements, but more observations have the potential to significantly improve the fidelity of the engineering models.

It would be prudent to instrument all Mars atmospheric flight missions to extract 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 (poorly 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.

A note regarding the current thinking about developing human scale landers. Since three to four landers would likely be delivered to the same location, precision landing and minimal jettison events are priorities. Additionally, common lander structure is desired to minimize cost and risk and the cargo landers would be delivered prior to the crew. Therefore, the baseline lander system will need to be designed to accommodate variations in payload mass, arrival season, etc. Unlike current robotic lander missions designed for a specific entry date and time, these vehicles will need to be more robust to architectural variations. Atmosphere variations will be one part of the dispersions considered in the design.

<u>Goal IV, Investigation A1.1:</u> At all local times, make long-term (>5 Mars 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 and a horizontal resolution of <10 km. (High Priority)

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

<u>Goal IV, Investigation A1.2:</u> At all local times, make long-term (>5 Mars 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 and a horizontal resolution of <10 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). (High Priority)

<u>Goal IV, Investigation A1.3:</u> Make long-term (>5 Mars 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 ≤100 km. The record needs to include a planetary scale dust event. (High Priority)

A better understanding of winds would help allow pinpoint landing of surface systems. In addition, there are currently essentially no global measurements of martian winds, a key component of the dynamical atmospheric system. Wind measurements would 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.

Goal IV, Sub-Objective A2: Characterize the orbital debris environment around Mars with regard to future human exploration infrastructure. (Low Priority)

Goal IV, Investigation A2.1: Develop and fly an experiment capable of measuring or constraining the primary meteoroid environment around Mars for particles in the threat regime (>0.1 mm). (Low 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. The nature of this material could be constrained through in situ measurements, meteoroid induced changes in the martian atmosphere, or monitoring of meteoroids from the surface. The model used in designing spacecraft destined for anywhere between Mercury and the asteroid belt between Mars and Jupiter is called the Meteoroid Engineering Model (MEM), version 3 (Moorhead et al. 2019). MEM 3 is adequate for the design of Mars mission, but more data would reduce the uncertainty, which is currently estimated to be about an order of magnitude at Mars' distance from the Sun (practically zero data or constraints). Reducing the uncertainty will likely cut down on the amount of shielding needed for spacecraft.

Goal IV, Sub-Objective A3: Assess landing-site characteristics and environment related to safe landing of human-scale landers. (Medium Priority)

Goal IV, Investigation A3.1: Characterize selected potential landing sites to sufficient resolution to detect and characterize hazards to landing human scale systems. (Medium Priority)

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.

Goal IV, Investigation A3.2: Determine physical and mechanical properties and structure (including particle shape and size distribution), cohesion, gas permeability, and the chemistry and mineralogy of the regolith, including ice contents. (Medium Priority)

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, MSL and InSight missions. This can lead to excavation of holes under the landers as well as the ejection of materials that can damage other systems at the landing site. Computational fluid dynamic modeling of human scale retro rocket plumes near landing show that the plume could impact the surface while the vehicle is still 100's of meters above the ground, and that, depending on engine cant angles and thrust levels just before landing, debris can be thrown up to 700 m from the landing site.

Goal IV, Investigation A3.3: Profile the near-surface winds (<15 km altitude) 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 pinpoint landing of surface systems. The winds are also a very sensitive diagnostic for the validation of numerical boundary layer models.

Goal IV, Objective B: Obtain knowledge of Mars sufficient to design and implement human surface exploration and EVA on Mars with acceptable cost, risk and performance.

After humans have landed on Mars, it will be imperative that surface operations, including extravehicular activities (EVA), are robust and capable enough to accomplish the mission objectives. Robotic exploration of the surface has greatly improved our knowledge of hazards for rovers and the nature of the surface materials. However, important gaps remain in our knowledge of how human systems may be affected by the martian surface environment.

Goal IV, Sub-Objective B1: 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 D2), the primary gaps in our knowledge about potential harmful environmental effects include the radiation environment and dust toxicity of surface regolith.

Goal IV, Investigation B1.1: Conduct measurements of neutrons with directionality (energy range from <10 keV to >100 MeV). (Medium Priority)

Goal IV, Investigation B1.2: 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 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 damaging 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 which is currently the situation with MAVEN and MSL. Unfortunately, the current solar activity is too low to generate energetic enough SEP events and the resulting outputs of the model system are not 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 continues to provide ground-truth measurements of the radiation environment on the surface of Mars, for both GCR and the SEP events. These measurements have been 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 had 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, there have been very few SEPs during the course of the MSL mission and the largest event measured thus far (10-12 September 2017) was still too small to represent a risk to the health of any astronaut receiving it (Zeitlin et al. 2018). Much larger SEP events are possible and their radiation impacts remain poorly understood.

<u>Goal IV, Investigation B1.3:</u> Assay for chemicals with known toxic effect on humans 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.). (Medium Priority).

<u>Goal IV, Investigation B1.4:</u> 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). (Medium Priority)

A sample return of typical martian surface materials will provide a wealth of knowledge about the potential toxic effects of Mars dust on humans. Dust mitigation protocols have already been adopted and are expected to address much of the risk.

Goal IV, Sub-Objective B2: Characterize the surface particulates that could affect engineering performance and lifetime of hardware and infrastructure. (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 B1 in this Goal, or the effect of dust on ISRU systems which is within Sub-Objective C1).

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): *(i)* astronaut walking, *(ii)* rover wheels spinning up dust, and *(iii)* landing and takeoff of spacecraft. These three mechanisms would also be relevant for a martian surface mission, but on Mars there would be a fourth as *(iv)* winds are capable of raising and transporting dust.

Addressing this Sub-Objective requires collecting enough data about the martian dust so as to be able to create a large quantity of a martian dust simulant that could be used in engineering laboratories on Earth. Such data would be best obtained by analysis of a returned sample. We have substantial knowledge of martian dust already and good simulants exist which is why this is ranked as a low priority.

Goal IV, Investigation B2.1: Analyze regolith and surface aeolian fines (dust), with a priority placed on the characterization of the electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations. (Low Priority)

Significant data about dust properties, dust accumulation rates, and effects on mechanical surface systems on Mars have been obtained from Mars Exploration Rovers missions (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.

Goal IV, Sub-Objective B3: Assess the climatological risk of dust storm activity in the human exploration zone at least one year in advance of landing and operations. (High Priority)

Dust storms pose a direct risk to human exploration of Mars in several ways. Landing systems are not currently planned on being robust to the presence of a significant dust storm, and thus it is imperative that dust storm forecasting be accurate enough to confidently rule out dust storm formation during landing. Furthermore, dust storms can significantly affect operations and degrade solar power collection, making storm forecasting during surface operations an important capability. Long-term (seasonal and annual) expectation of dust events can be established statistically. Accurate short-term forecasting (hours to sols) will require a combination of improved atmospheric models and an active network of monitoring weather satellites and surface-based meteorological stations to provide the synoptic data needed as input to any forecast model. Improved measurements of the near-surface atmosphere are critically needed to improve the accuracy of Mars atmospheric models (see Goal II, Sub-Objective A1).

Goal IV, Investigation B3.1: Globally monitor the dust and aerosol activity continuously and simultaneously at multiple locations across the globe, especially during large dust events, to create a long-term dust activity climatology (>10 Mars years) capturing the frequency of all events (including small ones) and defining the duration, horizontal extent, and evolution of extreme events. (High Priority)

Cross-cutting: Goal II: A1

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). Accurately measuring these conditions is critical to understanding the structure, and dynamical behavior of extreme weather on Mars.

Goal IV, Investigation B3.2: Monitor surface pressure and near surface (below 10 km altitude) meteorology over various temporal scales (diurnal, seasonal, annual), and if possible in more than one locale. (High Priority)

Cross-cutting: Goal II: A1

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. Such data 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.

Goal IV, Investigation B3.3: Collect temperature and aerosol profile observations even under dusty conditions (including within the core of a global dust storm) from the surface to 20 km (40 km in a global dust storm) with a vertical resolution of <5 km. (High Priority)

Cross-cutting: Goal II: A1

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

Goal IV, Sub-Objective B4: Assess landing-site characteristics and environment related to safe operations and 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.

Goal IV, Investigation B4.1: Characterize selected potential landing sites to sufficient resolution to detect and characterize hazards to trafficability at the scale of the relevant systems. (Medium Priority)

Goal IV, Investigation B4.2: Determine physical and mechanical properties and structure (including particle shape and size distribution), cohesion, gas permeability, and chemistry and mineralogy of the regolith, including ice contents. (Medium Priority)

These investigations mirror Investigations A3.1 and A3.2 but focus on collecting data needed for surface operations. While there are strong similarities, the surface systems and EVA requirements will require different data sets and analyses than the landers. 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 MER missions, 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.

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.

Eventual 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.

<u>Goal IV, Investigation B4.3:</u> 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 Mars year, both in dust devils and large dust storms. (Medium Priority)

Cross-cutting: Goal II: A1.2

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 conductive 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.

Goal IV, Objective C: Obtain knowledge of Mars sufficient to design and implement In Situ Resource Utilization of atmosphere and/or water on Mars with acceptable cost, risk and performance.

In situ resource utilization (ISRU) is a critical aspect of human exploration. Initial human missions are anticipated to be strongly dependent on atmospheric capture and conversion of CO_2 to O_2. Later missions could begin to rely more heavily on water collected either from the regolith or from buried ice. Much later missions could rely on construction materials derived from martian regolith. The initial human missions will provide substantial opportunities to explore for more extensive water resources and to experiment with martian materials for use in construction. This document encompasses the use of robotic flight missions (to Mars) to prepare for potential human missions (or sets of missions) to the martian system and therefore topics such as construction of large habitats and mining of precious/rare metals are not addressed here as they are not the target of initial human missions.

Goal IV, Sub-Objective C1: 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. ISRU has been a staple of human exploration architecture for Mars since the NASA Design Reference Missions of the 1990s.

Goal IV, Investigation C1.1: 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 yet 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 Mars-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 lower martian atmosphere is well-mixed, only a single advance measurement is expected to be needed.

Goal IV, Sub-Objective C2: Characterize potentially extractable water resources to support ISRU for long-term human needs. (Medium Priority)

The most important resource needed to support sustained human presence is water. Critical missing information falls into two broad categories: *(1)* the location and attributes (e.g., concentration, depth, chemistry, accessibility) 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.

The importance of ISRU using martian H_2O for human exploration of Mars is based on its ability to help sustain a long term human presence. It is the logical next step after the initial mission(s) and therefore it is of interest to ensure that sizable, extractable water resources are present near the first human landing sites. This will enable the first human missions to verify and begin the process of setting up water-based ISRU. Access to abundant water resources will be critical for enabling future missions and sustaining human exploration beyond the first mission. This investigation is rated as a medium priority because many of the key investigations are needed during the first human missions to the surface and a suitable deposit should be identified for landing site selection processes.

In the case of hydrogen (or equivalently, water), ISRU has the potential to have a substantial long term impact on mission affordability, particularly as related to the amount of mass to be delivered to the surface. 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 or buried glaciers, in the polar ice caps, 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, carbonate, 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. Investigations into subsurface ice may also have relevance for Goal I Investigation A2.1.

Goal IV, Investigation C2.1: Identify a set of candidate water resource deposits that have the potential to be relevant for future human exploration. (Medium 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.

Goal IV, Investigation C2.2: 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. (Medium Priority)

To prepare high spatial resolution maps, information needs to 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.

Goal IV, Investigation C2.3: Measure the energy required to excavate/drill and extract water from the H-bearing material, either shallow water ice or hydrated minerals as appropriate for the resource. (Medium Priority)

Goal IV, Objective D: Obtain knowledge of Mars sufficient to design and implement biological contamination and planetary protection protocols to enable human exploration of Mars with acceptable cost, risk and performance.

Human exploration will bring along with it much higher levels of contamination from terrestrial biota. It will also result in unprecedented exposure of humans to martian materials. Understanding and constraining the risk of these effects to both science and to the Earth is of major importance. The levels of exposure between the human environment and the martian surface will vary depending on exploration architecture. Certain types of human activities, related to mission architecture and areas of the surface being accessed, will result in greater likelihood of forward and backward contamination. Therefore the sub-objectives listed below should be interpreted based on the type of human activities occurring during surface exploration.

Goal IV, Sub-Objective D1: Determine the martian environmental niches that meet the definition of "Special Region" at the human landing site and inside of the exploration zone. (High Priority)

It is necessary to consider both naturally-occurring Special Regions and those that might be induced by envisioned (human-related) missions. (Special Regions are defined within Rummel et al. (2014).) One of the major mission objectives of a potential human mission would likely be to determine if and how life arose naturally on Mars.

Goal IV, Investigation D1.1: Identify the locations and characteristics of naturally occurring Special Regions, and regions with the potential for spacecraft-induced Special Regions. (High Priority)

Cross-cutting: Goal I: A

Data that contributes to the understanding of the location of extant Special Regions where martian life could exist is considered to be high priority as it is essential in the search for extant life (see Goal I, Objective A). Additionally, if a Special Region is created as a direct consequence of human presence, it has the potential to be contaminated with terrestrial life and complicate the search for martian life. Similarly, any naturally-occurring Special Regions need to be identified and protected from potential terrestrial contamination.

Goal IV, Sub-Objective D2: 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. (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.

Goal IV, Investigation D2.1: Determine if extant life is widely present in the martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard. (High Priority)

This Investigation would aid in reducing risks to acceptable, as-yet undefined, standards as they pertain to the human flight crew. The risks in question relate to the potential exposure of the human flight crew to martian material, such as regolith and dust, that would certainly be on the outside of the ascent vehicle, or within the cabin. 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.

The impact of the data from this Sub-Objective on mission design has been rated high as it is considered mission-enabling. 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.

Goal IV, Sub-Objective D3: Determine if martian materials or humans exposed to the martian environment are free, within acceptable risk standards, of biohazards that might have adverse effects on the terrestrial environment and species if returned to Earth. (Low Priority)

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. A step called "breaking the chain of contact" is necessary to manage this risk to avoid exposure of martian material to the Earth's ecosystem. 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 assess the hazard level in advance whether or not that dust is biologically hazardous in a terrestrial environment which can include inside of terrestrial organisms as well as in the Earth environment. The substantial delivery of material to the Earth from Mars through history makes it unlikely that small amounts of martian material would affect the terrestrial ecosystem which makes this a low priority investigation (PPIRB 2019).

Goal IV, Investigation D3.1: Determine the viability of terrestrial organisms when exposed to martian material under Earth-like conditions. (Low Priority)

Goal IV, Sub-Objective D4: Determine the astrobiological baseline of the human landing site prior to human arrival. (High Priority)

Humans will bring with them high levels of terrestrial contamination for the martian environment. Understanding the levels of contamination and how this contamination spreads across the surface is important for evaluating and adjusting exploration strategies moving forward. A critical aspect to determining the levels of contamination is to obtain comprehensive measurements of the environment prior to human arrival. This sets a baseline for the abundance of organic compounds and other biomarkers that might be used to track terrestrial contamination.

Goal IV, Investigation D4.1: Determine characteristics of the Mars atmosphere, surface, and sub-surface environments that constitute the astrobiological baseline of the landing site prior to the introduction of terrestrial bio-material. (High Priority)

Cross-cutting: Goal I: A

Goal IV, Sub-Objective D5: Determine the survivability of terrestrial organisms exposed to martian surface conditions to better characterize the risks of forward contamination to the martian environment. (Medium Priority)

Goal IV, Investigation D5.1: Determine the extent to which bio-material released by human exploration activities can be transported by wind and air-borne dust. (Medium Priority)

Goal IV, Investigation: D5.2: Determine the survivability of terrestrial organisms released at the surface under martian surface conditions and micro-environments created by human exploration elements. (Medium Priority)

Goal IV, Objective E: 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.

Goal IV, Sub-Objective E1: 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 selection of 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 unknown surface composition will drive science and exploration objectives and may also influence systems design.

Goal IV, Investigation E1.1: Determine the elemental and mineralogical composition as well as the physical and thermal properties of the surface and near sub-surface of Phobos and Deimos. (High Priority)

Goal IV, Investigation E1.2: Identify geologic units, their value for science and exploration, and their potential for future in situ resource utilization (ISRU) operations. (High Priority)

Goal IV, Investigation E1.3: 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. (High Priority)

Goal IV, Sub-Objective E2: Understand the conditions at the surface and in 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 in this Goal), 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.

Goal IV, Investigation E2.1: Measure and characterize the physical properties and structure of regolith on Phobos and Deimos. (High Priority)

Goal IV, Investigation E2.2: Determine the gravitational field to a sufficiently high degree to be able to carry out proximity orbital operations and rendezvous. (High Priority)

Goal IV, Investigation E2.3: Measure the electrostatic charge and plasma fields near the surface of Phobos and Deimos. (High Priority)

See Goal II, Sub-Objective A2 for description of the types of measurements of interest.

Goal IV, Investigation E2.4: Measure the surface and subsurface temperature regime of Phobos and Deimos to constrain the range of thermal environments of these moons. (High Priority)

Integrating Across the MEPAG Goals to Understand Mars and Beyond

The objectives, sub-objectives, and investigations discussed in the previous chapters are divided by Goal, but it is often at the intersections between Goals that overarching questions are addressed. Here we discuss five overarching questions in Planetary Science (presented in no particular order) that were compiled by MEPAG, in response to a request by the NASA Planetary Science Division Director (July 2019):

- How do planetary surfaces, crusts, and interiors form and evolve?
- How do climates and atmospheres change through time?
- What are the pathways that lead to habitable environments across the solar system and the origin and evolution of life?
- How is the solar system representative of planetary systems in general?
- What is needed for humans to explore the Moon and Mars?

The first three of these overarching questions are very similar to the questions discussed in this chapter within the 2015 MEPAG Goals Document (and repeated in the 2018 version), which were traceable to the *Vision & Voyages'* cross-cutting science themes of building new worlds, planetary habitats, and solar system workings (NRC, 2013). The fourth reflects the growing interest and capability in understanding the range of diversity in planetary systems (including planetary body variation within those planetary systems) that exists in our universe. The fifth comes from the long-standing drive for humans to access, explore, and potentially inhabit another planet, with Mars being a prime target for that endeavor.

How do planetary surfaces, crusts, and interiors form and evolve?

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. For example:

- In the ancient martian climate, fluivial, lacustrine and possibly oceanic processes may have dominated surface evolution as they do now on Earth. Within the present martian climate, volatile accumulation/sublimation and winds are dominant drivers for landscape evolution. While this is differs from the dominant geomorphic processes on Earth, the martian environment may share many processes and resultant landforms with icy worlds, such as Pluto, Triton, Europa, Titan and Ceres, and thus can serve as a natural "laboratory" for quantitatively studying sublimation-driven processes so as to refine and calibrate related theoretical physics models. Similarly, Mars also serves as a good comparative planetology basis for testing wind and sediment lofting/transport models and determining how aeolian dynamics operate within a low-density (but not negligible) atmosphere. In these and other investigations of past and modern Mars processes, Goals II and III investigations relate to the connections drawn between processes and their surface and near-surface environmental/meteorological drivers.
- There are also valuable comparisons to be considered with Venus, such as types of volcanism, new evidence for magma evolution and igneous diversity on both planets, and

how lava type and flow are influenced by planetary conditions; interactions with the solar wind. Titan provides comparisons regarding sand dune migration and evolution, fluvial processes, and cryosphere evolution. The Moon provides a comparative surface to study impactor flux variation through the solar system. All these topics are relevant to habitability and solar system formation and are applicable to exoplanet studies – see below, and rely upon investigations described within Goals I, II, and III.

- Unlike the Earth, Mars has no plate tectonics. Contrasting the martian interior structure and heat flux with that on Earth, Europa or Venus (which may also have no current plate tectonics, but which has undergone massive crustal disruption and recycling) can yield clearer pictures of how a planetary body forms and evolves – which clearly connects to Goal III Objectives but also has strong implications for habitability (Goal I) and climate evolution (Goal II).

How do climates and atmospheres change through time?

Orbital, landed, laboratory (including meteorite studies and other kinds of experiments), and modeling studies have shown that Mars has experienced a massive loss of atmosphere, quasi-periodic shifts in its rotational axis leading to cycling of where water and CO_2 ice are stored on or near the surface as ice, and variations in surface pressure, as well as quasi-periodic variations in atmospheric dust flux, including planet-encircling dust storms. These and many other factors have led to climate shifts on many time scales, which have resulted in atmospheric compositional changes and the formation/modification/removal of climate records within rocky and icy landforms and the subsurface. Truly understanding the implications of individual climate and climate record-focused Objectives and Investigations for martian life, climate, and geology requires understanding a myriad of environmental condition and process interactions and interdependencies. 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? Compared to Earth, Mars is a simpler version of a terrestrial atmosphere. As such, it presents us with an alternate laboratory to understand how climate systems evolve. The record preserved in the PLD may be a crucial Rosetta Stone for how this similar (but different) climate has responded to orbitally induced insolation changes, and how other processes may overlie that and influence the system's behavior. By understanding not only how Earth's climate works, but also that of Mars, we will take a long stride toward understanding terrestrial climates in general.
- The excellent record preserved on Mars of early surface and subsurface environments without an extensive biosphere provides a critical counterpoint to early Earth geologic records of atmosphere, climate, and biologically-driven atmospheric change. Goal III includes investigations to constrain the surface chemistry and climates on ancient Mars and determine the links to ancient atmosphere and climate evolution that are a major focus of Goal II. Ulimately, these studies will inform Goal I as it feeds into questions regarding how

biological communities are affected by, but also alter, the environments produced by climate and geological processes. That ancient surface may also inform Goal I aas to the nature of prebiotic organic chemical evolution, in marked contrast to the Earth where life and plate tectonics may have erased that portion of our planet's history.

What are the pathways that lead to habitable environments across the solar system and the origin and evolution of life?

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 biosignature-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 from the ancient past through to the present, 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; and evaluating the changing nature and magnitude of oxidative or radiation hazards at the surface and in the shallow crust.

How is our solar system representative of planetary systems in general?

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 we have space-age observations of them provides provocative new insights into our study of Earth. Furthermore, the discovery of countless planets (of all sizes and types) within extrasolar systems has broadened the driving questions and added impetus to these investigations. Studies of Mars can contribute much to this area. 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.
- Within the solar system, the variation in the four rocky planets (Mercury, Venus, Earth, Mars) is reflective of the variation we see in the universe. Understanding more about how Mars formed and evolved, and why it's different from the other three (including with regards to habitability, see above), will enhance the ability to interpret planets found around a different star.
- Mars is the only rocky planet in our solar system with an intact, active geologic record from its first billion years, making it a valuable resource for studies of early planet evolution and impact rates.
- Mars' unique geologic record, its recent past documented in the PLD, and its current atmosphere comprise another example of how a terrestrial planet's climate may form, evolve and behave under current and past conditions. To deepen our ability to understand the breadth of possible planetary climates (including exoplanets), Mars represents a unique opportunity to compare Earth's climate (both current and past) with another terrestrial planet's climate, and thus understand the response of climate systems to various changes.

What is needed for humans to explore on the Moon and Mars?

To design missions for sending humans to Mars' surface with acceptable risk and cost, we need to understand how Mars is (or is not) similar to the environments within which humans generally live. The information needed to establish the resources that Mars can provide for in situ exploitation by humans is much the same as that needed to understand Mars as a system, whether it is or was habitable or inhabited, and why it and the other planets are as they are. The first steps toward humans exploring Mars will require more robotic Mars exploration, and once humans are there, scientific exploration can benefit from their presence.

As NASA is now looking to send humans back to the Moon and eventually on to Mars, we may be able to leverage investments in human safeguards to survive on the Moon for use at Mars. For example, both places are incredibly dusty with demonstrated hazards already understood for the Moon, and expected to be similar, if not worse at Mars (e.g., dust storms, dust devils). For both exploration targets, not only will we need to contend with low or no atmospheric pressure, but also dust that can damage seals and contact surfaces. In Situ Resource Utilization efforts at the Moon may help us more quickly develop similar systems for Mars. Capabilities to protect humans against cosmic rays for extended lunar stays will be directly applicable to eventually reaching Mars. As we reach out to these two bodies most likely to be within landed reach of humans in the near future, many of the techniques developed for one would serve both targets. As a result, an additional synergy between lunar and martian exploration is the increased pace expected for lunar missions, and the relatively low latency in conducting science there, making the Moon a efficient development ground for some future Mars mission instruments.

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

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

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

Goodliff, Kandyce E., Patrick Troutman, Douglas A. Craig, Jose Caram, and Nicole Herrmann. "Evolvable Mars Campaign 2016 - A Campaign Perspective." In *AIAA SPACE 2016*. American Institute of Aeronautics and Astronautics. Accessed December 19, 2019. https://doi.org/10.2514/6.2016-5456.

(All MEPAG Goals Documents can be found at 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.

MEPAG (2018), Mars Science Goals, Objectives, Investigations, and Priorities: 2018. D. Banfield, ed., 81 p. white paper posted October, 2018.

Moorhead, Althea V., Aaron Kingery, and Steven Ehlert. "NASA's Meteoroid Engineering Model 3 and Its Ability to Replicate Spacecraft Impact Rates." *Journal of Spacecraft and Rockets* (2019). https://doi.org/10.2514/1.A34561

NASA Human Exploration Strategic Plan 2019, retrieved on Jan 13, 2020 from https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_09-16-2019.pdf

National Academies of Sciences, Engineering, and Medicine 2018. Review and Assessment of Planetary Protection Policy Development Processes. Washington, DC: The National Academies Press. https://doi.org/10.17226/25172.

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.

PPIRB (2019) NASA Planetary Protection Independent Review Board (PPIRB), Final Report, *Chaired by A. Stern.* https://www.nasa.gov/sites/default/files/atoms/files/planetary_protection_board_report_20191018.pdf

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., Beaty, D.W., Jones, M.A., Bakermans, C., Barlow, N.G., Boston, P.J., Chevrier, V.F., Clark, B.C., de Vera, J.P.P., Gough, R. V., Hallsworth, J.E., et al., 2014. A new analysis of Mars ‘‘special regions”: findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). Astrobiology 14 (11), 887–968.

Zeitlin, C., D. M. Hassler, J. Guo, B. Ehresmann, R. F. Wimmer-Schweingruber, S. C. R. Rafkin, J. L. Freiherr von Forstner, et al. “Analysis of the Radiation Hazard Observed by RAD on the Surface of Mars During the September 2017 Solar Particle Event.” *Geophysical Research Letters* 45 (June 1, 2018): 5845–51. https://doi.org/10.1029/2018GL077760.

App. 2: Acronyms used

DRA	Design Reference Architecture
EDL	Entry, Descent, Landing
EPS	Extracellular Polymeric Substances
ESA	European Space Agency
GCR	Galactic Cosmic Rays
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (mission)
IR	Infrared
ISRU	In situ resource utilization
MAVEN	Mars Atmospheric and Volatile Evolution (mission)
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
NPLD	North Polar Layered Deposits
NRC	National Research Council
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
SPLD	South Polar Layered Deposits
SRP	Supersonic Retro-Propulsion
TGO	Trace Gas Orbiter (mission)
UV	Ultraviolet

App. 3: Goal I Supplemental Information

1. THE NEED FOR WORKING MODELS

The specific approach and methods involved in the search for evidence of life beyond Earth and the study of abiotic organic chemical evolution depend critically on how prebiotic chemistry, life, habitability, and biosignatures are conceived. Such efforts must confront the potential for bias and "tunnel vision" that arises from having only terrestrial life and processes on which to base our models. Efforts should accommodate the possibility for exotic organisms that may differ in biochemistry, morphology, or ecology. Nonetheless, working concepts of prebiotic chemistry, life, habitability, and biosignatures must be adopted in order to define what measurements should be made in targeting and executing a search for evidence of life. Below, these concepts are discussed in specific reference to Mars exploration and the strategy outlined in this document.

1.1. 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 in Objective A.

1.2. 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. 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) (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.

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.

1.3. Habitability

Life on Earth has colonized every environment where liquid water is present, with few but notable exceptions such as the saturated $CaCl_2$ brine in Don Juan Pond, Antarctica. Liquid water is the medium that allows organisms to reach homeostasis, and it is also the agent that chemically alters rocks and dissolves atmospheric gases, providing those organisms with access to essential elements and nutrients, as well as potential sources of chemical energy. Therefore, an environment that contains liquid water has a high potential to sustain life, but examples like Don Juan Pond show that additional metrics are needed to truly resolve habitability.

Such additional metrics, outlined below, allow to resolve habitability as a continuum (i.e., more habitable, less habitable, uninhabitable), and to assess the relative potential of different environments to express (i.e., generate) biosignatures. 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 beyond the presence of liquid water:

- 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 IR 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.

Sufficiency in habitability assessments to search for evidence of life

The search for evidence of life must be tied to a habitability assessment. The extent of that assessment (i.e., the number of parameters considered) depends on the amount of risk that the program can tolerate. At a minimum, habitability assessments that include empirical evidence of liquid water activity ought to satisfy a search for evidence of life in the context of the extent and duration of that liquid water activity. This constitutes an inherently "binary" threshold to support a search for evidence of life – liquid water is/was either present or not. Empirical evidence could include the presence of chemical sediments (e.g., salts, phyllosilicates) and their stratigraphic relations, measurements of stable isotopic composition of water ice, chemical gradients in regolith indicative of liquid transport of soluble ions or other in situ measurements.

The working model and rationale described above 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.

1.4. Biosignatures

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) Chemical: 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) Structural: 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. 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.

3) Physiological: Metabolically active organisms display behaviors that are difficult to mimic in the abiotic world. For example, many organisms can move with speed and directionality towards or away from specific stimuli such as light or high/low concentrations of certain chemicals. Metabolically active organisms can also carry chemical reactions with extremely high catalytic speeds. The same chemical reactions are typically sluggish in abiotic systems under ambient conditions. An additional hallmark of metabolic chemical reactions is selectivity towards products and reactants, which may manifest as 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. These manifestations of biological activity are aimed at maintaining an optimal physiological state in response to environmental conditions or environmental change. Manifestations of physiological activity can be powerful biosignatures, but they can also result in ambiguous signals in environments that are chemically reactive, particularly if life is present at extremely low abundances. This was best exemplified by the Viking biological experiments. Dead or dormant organisms would fail to generate physiological biosignatures, and this could lead to false negative interpretations. Given the potential for false negatives and ambiguous results, and taking into consideration that extant forms of life on Mars would likely be present at very low abundances (amid water, energy and nutrient limitations), the search for physiological biosignatures as part of Goal I sub-objective A is given a lower priority.

The need for multiple lines of evidence

Biosignature detection can be exceedingly difficult in environments where life is present at very low abundances or only in fossilized form. Fossil biosignatures are also often degraded due to chemical and physical alteration, which compounds the problem of biosignature detectability and interpretation. For these reasons, efforts to search for evidence of life ought to cast the broadest net possible and target multiple lines of evidence. This includes searching for multiple, independent biosignatures that together reinforce the interpretation of each individual measurement. For example, measurements of enantiomeric excess in biochemical building blocks together with compound-specific isotopic analyses is significantly more diagnostic than either measurement individually. Seeking multiple lines of evidence also implies providing adequate environmental context through analyses of habitability factors and biosignature preservation potential.

Sufficiency in preservation potential assessments to search for evidence of life

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 aspect 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.

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

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

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

The problem of contamination

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 detection 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.

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App. 4: Goal III Mapping Between 2018 & 2020 Versions

2020 Version	Links to 2018 Version				
A1.1 Determine the modern extent & volume of liquid water & hydrous minerals within the crust.	A1.4	A1.2	A4.1	A4.3	
A1.1 Identify the geologic evidence for the location, volume, & timing of ancient water reservoirs	A1.1	A1.3	A4.2		
A1.3 Determine the subsurface structure & age of the polar layered deposits, & identify links to climate.	A1.4	A3.1	A4.1	A4.2	A4.3
A1.4 Determine how the vertical & lateral distribution of surface ice & ground ice has changed over time.	A1.4	A3.3	A4.2		
A1.5 Determine the role of volatiles in modern dynamic surface processes, correlate with records of recent climate change, & link to past processes & landforms.	A1.1	A1.4	A3.1	A3.3	
A2.1 Constrain the location, volume, timing, & duration of past hydrologic cycles that contributed to the sedimentary & geomorphic record.	A1.1	A4.3			
A2.2 Constrain the location, composition & timing of diagenesis of sedimentary deposits & other types of subsurface alteration.	A1.2	A1.3			
A2.3 Identify the intervals of the sedimentary record conducive to habitability & biosignature preservation.	A1.1	A1.3	A4.1		
A2.4 Determine the sources & fluxes of modern aeolian sediments.	A1.1	A3.1	A3.3		
A2.5 Determine the origin & timing of dust genesis, lofting mechanisms, & circulation pathways.	A1.6	A3.1			
A3.1 Link geologic evidence for local environmental transitions to global-scale planetary evolution.	A1.1	A4.1			
A3.2 Determine the relative & absolute age, durations, & periodicity of ancient environmental transitions.	A4.1				
A3.3 Document the nature & diversity of ancient environments & their implications for surface temperature, geochemistry, & aridity.	A1.1	A1.3			
A3.4 Determine the history & fate of sulfur & carbon throughout the Mars system.	New				
A4.1 Determine the absolute & relative ages of geologic units & events through martian history.	A4.5				
A4.2 Constrain the effect of impact processes on the martian crust & determine the martian crater production rate now & in the past	A1.7	A2.2	A3.1		
A4.3 Link the petrogenesis of martian meteorites & returned samples to the geologic evolution of the planet.	New				
A4.4 Constrain the petrology/petrogenesis of igneous rocks over time.	A1.3	A1.5			
A4.5 Determine the surface manifestation of volcanic processes through time & their implications for surface conditions.	A1.3				
A4.6 Develop a planet-wide model of Mars evolution through global & regional mapping efforts.	A1.2	A1.3	A2.3		
B1.1 Determine the types, nature, abundance & interaction of volatiles in the mantle & crust, & establish links to changes in climate & volcanism over time.	B1.1				
B1.2 Seek evidence of plate tectonics-style activity & metamorphic activity, & measure	B1.2				
B2.1 Characterize the structure & dynamics of the interior.	B2.1				
B2.2 Measure the thermal state & heat flow of the martian interior.	B2.2				
B2.3 Determine the origin & history of the magnetic field.	B2.3				
C1.1 Determine the thermal, physical, & compositional properties of rock & regolith on the moons.	C1.1				
C1.2 Interpret the geologic history of the moons, by identification of geologic units & the relationship(s) between them.	C1.2				
C1.3 Characterize the interior structure of the moons to determine the reason for their bulk density & the source of density variations within the moon (e.g., micro- vs. macroporosity).	C1.3				
C2.1 Understand the flux of impactors in the martian system, as observed outside the martian atmosphere.	C2.1				
C2.2 Measure the character & rate of material exchange between Mars & the two moons.	C2.2				

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