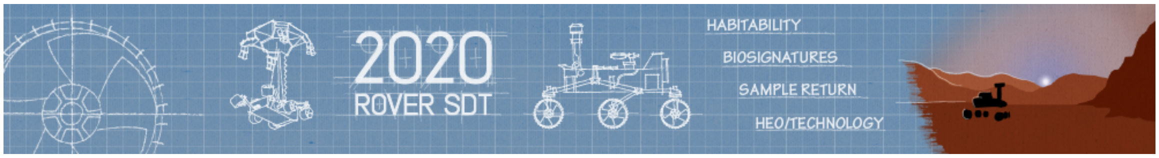

Report of the Mars 2020 Science Definition Team

J.F. Mustard, chair; M. Adler, A. Allwood, D.S. Bass, D.W. Beaty, J.F. Bell III, W.B. Brinckerhoff, M. Carr, D.J. Des Marais, B. Drake, K.S. Edgett, J. Eigenbrode, L.T. Elkins-Tanton, J.A. Grant, S. M. Milkovich, D. Ming, C. Moore, S. Murchie, T.C. Onstott, S.W. Ruff, M.A. Sephton, A. Steele, A. Treiman

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or

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Inquiries regarding this report should be directed to Jack Mustard, SDT Chair (John_Mustard@brown.edu), David Beaty, MED Chief Scientist (David.W.Beaty@jpl.nasa.gov), or Mitch Schulte, NASA SMD (mitchell.d.schulte@nasa.gov)

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1 Executive Summary

The Mars 2020 Science Definition Team (SDT) has outlined a mission concept for a science-focused, highly mobile rover to explore and investigate in detail a site on Mars that likely was once habitable. The SDT-preferred mission concept employs new *in situ* scientific instrumentation in order to seek signs of past life (had it been there), select and store a compelling suite of samples in a returnable cache, and demonstrate technology for future robotic and human exploration of Mars. The mission concept fully addresses the requirements specified by NASA in the SDT charter while also ensuring alignment with the recommendations of the National Academy of Sciences Decadal Survey for Planetary Science (Visions and Voyages, 2011).

Key features of the integrated science mission concept include:

- Broad and rigorous *in situ* science, including seeking biosignatures
- Acquiring a diverse set of samples intended to address a range of Mars science questions and storing them in a cache for potential return to Earth at a later time
- Improved landing technology to allow unprecedented access to scientifically compelling geological sites
- Collection of critical data needed to plan for eventual human missions to the martian surface
- Maximizing engineering heritage from NASA's successful Mars Science Laboratory (MSL) mission to constrain costs

The successful landing of the Curiosity science rover on August 6, 2012 was the latest in a series of technological and scientific triumphs of NASA's Mars Exploration Program. The prime focus of the exploration of Mars in the coming decade is to assess if life is or was present on Mars (NRC 2011, p.142). As scientific knowledge of Mars grows, it is becoming increasingly evident that portions of the martian surface were formerly habitable. Major uncertainties remain such as when and where those conditions prevailed, for how long, whether some form of life ever took hold, and if so whether any evidence of it has been preserved.

Addressing questions about habitability and the potential for life on Mars requires visiting a site with a geologic record that suggests both past habitability and a high probability to have preserved evidence of past life, had it occurred there, would still be preserved. The search for such a site will require a combination of orbiter and ground observations to measure a wide range of surface properties, such as elemental chemistry, mineralogy, surface texture and structure, at a wide range of scales. The geologic record then must be explored for signs of past life. This can be done *in situ* at Mars only in a preliminary sense. Definitive detection of past life would require analysis of samples here on Earth given the likelihood that such life would have occurred only in microbial form. A logical next step in the Mars program is therefore to prepare the way for sample return.

The chartering document of the 2020 Mars Rover Science Definition Team (SDT) contains a clear rationale to continue the pursuit of NASA's plans for "*Seeking the Signs of Life*". It also calls for a mission that enables concrete progress toward sample return, thereby satisfying the Planetary Decadal Survey science recommendation for the highest priority large mission for the decade 2013-2022. Combined with the intent to make progress toward future human exploration of Mars, the formal SDT charter presents a set of four primary objectives:

A. Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability.
B. Assess the biosignature preservation potential within the selected geological environment and search for potential biosignatures.
C. Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth.
D. Provide an opportunity for contributed Human Exploration & Operations Mission Directorate (HEOMD) or Space Technology Program (STP) participation, compatible with the science payload and within the mission's payload capacity.

The Mars 2020 SDT was chartered to formulate a mission concept, based on the MSL/Curiosity rover systems, which would address these four objectives within a cost- and time-constrained framework. The membership of the SDT (selected by NASA from over 150 applicants) consisted of scientists and engineers who represent a broad cross section of the Mars and planetary science communities with expertise that includes astrobiology, geophysics and geology as well as instrument development, science operations and mission design. The SDT addressed the four objectives and seven charter-specified tasks independently and methodically, specifically looking for synergy among them.

There is both independent and interconnected reasoning within the four objectives. Objectives A (assessment of past habitability) and B (assessment of biosignature preservation) are each ends unto themselves, while Objective A is also the means by which samples are selected for Objective B, and together they motivate and inform Objective C (demonstrate progress toward sample return). Objective D and its prioritized goals are themselves well aligned with A through C.

Critically, Objectives A, B, and C as an ensemble brought the SDT to the conclusion that exploration oriented toward astrobiology and the preparation of a returnable cache of carefully selected and documented surface samples is the only acceptable mission concept. Each objective was pursued with independent reasoning unique to its intent, but the conclusions together create a consistent, compelling, and attainable mission.

Exploring an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability as called for in **Objective A**, yields *in situ* science. This is optimized when the coverage, scale, and fidelity of the measurements, along with orbital observations, are combined in way that maximizes understanding of geologic context. Some records of habitability may not be preserved or detectable. ***Thus, the inability to detect geologic evidence for all four habitability factors (raw materials, energy, water, and favorable conditions) does not preclude interpretation of a site as a past habitable environment.*** A key strategy for interpreting past habitability is to seek geochemical or geological proxies for past conditions, as recorded in the chemistry, mineralogy, texture, and morphology of rocks.

Five measurement types constitute threshold (i.e. minimum) requirements to effectively and efficiently characterize the geology of a site and assess past habitability: 1) context imaging, 2) context mineralogy, 3) fine-scale imaging, 4) fine-scale mineralogy, and 5) fine-scale elemental chemistry. We propose that the measurements be nested and co-aligned.

Assessing the biosignature preservation potential within a formerly habitable environment and searching for potential biosignatures as called for in **Objective B** begins with the *in situ* measurements necessary to identify and characterize promising outcrops. Confidence in interpreting the origin(s) of potential biosignatures increases with the number of them identified and with a better understanding of the attributes and context of each. However, ***thorough characterization and definitive discovery of martian biosignatures would require analyses of samples returned to Earth***. While the SDT determined that actual detection of organics is not required for returning samples to Earth, other valuable attributes also might qualify sample(s) for return, e.g., the presence of other categories of potential biosignatures or evidence of high preservation potential in past habitable environments.

Accordingly the SDT recognizes six field measurement types as threshold requirements to support the search for biosignatures: 1) context imaging, 2) context mineralogy, 3) fine-scale imaging, 4) fine-scale mineralogy, 5) fine-scale elemental chemistry, and 6) organic matter detection. The first five threshold measurements are identical with those of Objective A, and in this case organic matter detection is added.

The SDT considered various ways to demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth, as called for in **Objective C**. The SDT concurs with the detailed technical and scientific arguments articulated by the National Research Council (NRC) Decadal Survey (2011) and MEPAG (most recently summarized in E2E-iSAG, 2012) regarding the critical role returned samples would play in the scientific exploration of Mars. *Thus,* ***significant technical progress by the Mars 2020 rover mission towards the future return of samples to Earth demands assembly of a cache of scientifically selected, well-documented samples packaged in such a way that they could be returned to Earth.*** Any version of a 2020 rover mission that does not prepare a returnable cache would seriously delay any significant progress toward sample return. With anything less, the flight of a sample-collecting rover would need to be repeated.

The SDT concludes that the threshold science measurements necessary to select and document samples for caching are the same as those of Objective A, with organic matter detection included as a baseline measurement.

Providing an opportunity for contributed HEOMD or Space Technology Program participation, compatible with the science payload and within the mission's payload capacity, as called for in Objective D, spans a range of options. Three classes of environmental measurements are needed to support HEOMD's long-term objectives: architecture drivers (*in situ* resources, atmospheric measurements for EDL, etc.), crew safety (surface radiation, material toxicity, etc.) and operational issues (surface hazards, dust, electrical properties, etc.). Importantly, measurements that address Objectives A, B, and C have direct relevance and application to already-established HEOMD strategic knowledge gaps. At the highest level, however, the value of a returnable cache is amplified because samples would address the HEOMD objectives related to biohazards, dust properties and toxicity, as well as regolith chemistry and mineralogy. The SDT recognized important opportunities for potentially valuable technology development on the Mars 2020 rover mission in the areas of improved landing site access, improved science productivity, and risk reduction. ***The SDT determined that HEOMD's proposed contribution to the Mars 2020 mission, a*** CO_2 ***capture and dust characterization payload that incorporates both dust analysis and weather measurements, could be accommodated and would be synergistic with the highest priority science objectives. The SDT also determined that the entry and descent phases of the 2020 mission should be characterized by a system with improvements over the MEDLI system that flew on MSL.***

To implement these objectives, the SDT considered a number of paths along which the Mars Exploration Program (MEP) could proceed, within the constraints placed by the envelope of available resources. This envelope includes the specific resources available for scientific instruments, as well as the supporting infrastructure and elements of a rover mission. Although the SDT was not charged to examine total mission costs but only to consider instrument costs and accommodation, the team sought throughout our deliberations to maximize the science return without requiring overly complex or incompatible mission elements that would potentially impart excessive costs or technical and scientific risk.

The SDT concluded that in order to properly address Objectives A, B, and C, the capability to conduct lateral and stratigraphic surveys and analyses at multiple spatial scales on many targets is required. This demands a capable rover (Curiosity-class) equipped to make the following set of proposed measurements.

- Context mineralogy
- Context imaging
- Fine-scale mineralogy
- Fine-scale elemental chemistry
- Fine-scale imaging
- Fine-scale organic detection/characterization

This suite of measurements, which ranges from context to fine scale, can be implemented to provide coordinated and nested measurements of the landing site. Key science advances would be made possible through coordinated measurements at complementary scales, including fine-scale measurements previously unavailable.

The SDT evaluated a range of potential instrument options that would meet the measurement priorities, and as an existence proof, assembled two hypothetical suites of instruments that would constitute a notional payload on the Mars 2020 rover. Using a broad array of published resources and results of recent planetary instrument meetings, ***the SDT concluded that a variety of instrument and implementation options could satisfy the proposed measurement types within the available budget constraints. Furthermore, there are several instruments with dual functionality.*** This provides valuable flexibility in arriving at a final payload through a competitive selection process.

An important conclusion of the SDT is that all four objectives can be fulfilled by a single rover carrying a modest but highly capable payload that includes the capacity to produce a returnable cache. In addition to adhering to the NRC Decadal Survey recommendations (2011) and moving science forward significantly, this mission would substantially enhance the synergy between SMD and HEOMD within NASA, and would be a worthy successor to Curiosity. For the first time, humanity would seek to collect samples with possible evidence of past martian life for analysis on Earth, where cutting edge techniques available now, as well as awaiting future development, could be applied to the search. This endeavor would be a major historic milestone worthy of a great national space program.

The SDT assessed the capabilities demanded of the rover flight system for science payload support. These include a system to collect samples for caching, a caching system, a mechanism for maintaining sample integrity, methods for sample processing, encapsulation and transfer, and the rock surface preparation capabilities needed for optimal science measurements. ***The caching system should have the capacity to acquire 31 samples. The rock surface preparation tool should have dust and rock-material removal capability comparable to the Rock Abrasion Tool (RAT) on MER but with an extended operational lifetime. To preserve the scientific value of cached samples they require encapsulation and sealing.***

The mission concept developed by the SDT included consideration of operations and strategies on Mars to achieve Objectives A, B, C, and D. Based on experience with past and ongoing rover missions and the unique characteristics of Mars 2020, we evaluated the trade space defined by the time needed for *in situ* science, coring and caching, and driving to and between regions of interest. ***The most scientifically valuable returnable cache would be achieved by developing the payload and spacecraft systems with consideration of increasing both the time available for science activities, and the productivity during that time.***

The SDT carefully considered landing sites in the context of the science and technology goals for 2020. Narrowing the size of the landing site error ellipse was a top priority for the success of Mars 2020. ***The SDT concluded that the technologies associated with a range trigger should be a threshold capability***

and strongly encourage inclusion of Terrain Relative Navigation (TRN) as highest priority baseline capability to help ensure access to high priority sites and reduce science risk related to site selection. The dual objectives for Mars 2020 – to provide access to astrobiologically relevant materials and cache samples for possible return to Earth at a later date – have not been attempted before, and these challenges place requirements on the landing site selection process that would differ from those for previous missions. Moreover, successful implementation of this mission concept would impact significantly the next several Mars missions, thereby warranting input on the landing site that extends beyond the Mars 2020 mission proper.

Prior landing site selection activities have not included discussion of access to samples for caching, nor associated trades between the potential merits of various sites and issues related to, e.g., EDL capabilities and required traverse distances for sample access. ***Deliberations on the science merits of possible landing sites for 2020 require the broad expertise of the science community to ensure a range of sites is proposed, considered, and comprehensively evaluated to maximize the likelihood that the 2020 rover can achieve its mission objectives and address the goals of Mars sample return.***

The SDT's evaluation of the 2020 opportunity for Mars finds that *pioneering Mars science can be accomplished within the available resources* and that *the mission concept of a science caching rover*, *if implemented, would address the highest priority, community-vetted goals and objectives for Mars exploration*. It would achieve high-quality science through the proposed suite of nested, coordinated measurements and would result in NASA's first Mars mission configured to cache samples for possible return to Earth at a later date.

Finally, sending this rover in 2020 benefits from NASA's investment in human capital, technology, and infrastructure at Mars. It builds on the scientific discoveries of the Mars Exploration Program, from evidence of liquid water in the past, to ancient habitable environments, to finding those places that have a high potential for preserving signs of past life. The opportunity is now, through this mission, to create a legacy for future generations of scientists and explorers.

2 Introduction

2.1 Introduction to the Mars 2020 Science Definition Team

The specific impetus for this study and resulting report began with a presentation by Dr. John Grunsfeld at the meeting of the American Geophysical Union (AGU), Dec. 3-7, 2012 in San Francisco. In a townhall-style presentation, Dr. Grunsfeld announced NASA's desire to organize a Mars rover mission to be launched in 2020, and to begin the planning process by forming a science definition team. During the following six weeks, a charter for the SDT was prepared, an SDT chair was recruited (Dr. Jack Mustard, Brown University), and a "dear colleague" was sent to the community to solicit volunteers by means of submitting a letter application. NASA evaluated the applications, and selected two teams: 1). The SDT itself, and 2). An independent assessment team (informally known as the "Red Team") to provide review services to the SDT, as well as independent evaluations to NASA. The SDT held its kick-off telecon on Jan. 24, 2013. The SDT was asked to deliver a PowerPoint-formatted report of its findings by May 31, and to deliver its final text-formatted report (this document) by July 1, 2013. Between Jan. 24 and July 1, the team held weekly teleconferences with significant intervening e-mail exchange. The team also met twice face-to-face, once at Goddard Space Flight Center, and once at the Jet Propulsion Laboratory. In addition to the competitively selected members of the SDT and Red Team, a number of experts were consulted (see the Acknowledgements section of this report for a listing), most importantly about 10 members of the Mars 2020 pre-project/project team at JPL (they were organized as a pre-project when SDT began, but became a project mid-course).

The overall SDT timeline is illustrated in Figure 2-1. The "dear colleague" letter used to solicit the team and the SDT's charter are contained in Appendices 1 and 2. The members of both the SDT and the Independent Assessment Team are listed in Appendix 2.

The charter specifies three general things (Appendix 1): 1). A set of objectives, 2). A set of assumptions and guidelines, and 3). A statement of task:

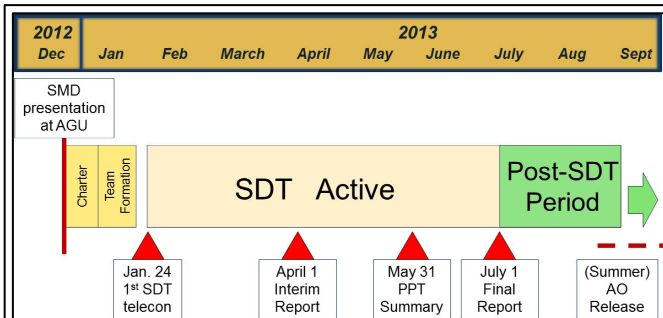


Figure 2-1. Timeline of Mars 2020 SDT Implementation Process*. The process began in December 2012, with the announcement at the AGU conference that NASA would propose to fly a mission to Mars, based on the Curiosity rover design, in 2020. The SDT was formed in late January, and has completed its report on July 1, 2013, preparatory for the release of the AO for the Mars 2020 rover mission.*

Charter-specified objectives list:

1. Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability and potential preservation of possible biosignatures.
2. *In situ* science: Search for potential biosignatures within that geological environment and preserved record.
3. Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth.
4. Provide an opportunity for contributed HEOMD or Space Technology Program (STP) participation, compatible with the science payload and within the mission's payload capacity.

In evaluating these objectives, the SDT found it more convenient to rephrase/reorganize them slightly as follows:

Charter-specified Mission Objectives:

A. Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability.

B. Assess the biosignature preservation potential within the selected geological environment and search for potential biosignatures.

C. Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth.

D. Provide an opportunity for contributed HEOMD or Space Technology Program (STP) participation, compatible with the science payload and within the mission's payload capacity.

Charter-specified assumptions/guidelines:

1. Launch in 2020.
2. The instrument cost would have a nominal limit of $100M (including margin/reserves). The division of the budget suggests an investment of $80M for US instruments and $20M for contributed elements.
3. Surface operations costs and science support equipment (e.g., an arm) would not be not included in the above limits.
4. The 2020 SDT should assume that the mission would utilize MSL SkyCrane EDL flight systems and Curiosity-class roving capabilities.
5. The mission lifetime would be one Mars year (~690 Earth days).
6. The SDT should work with the 2020 mission pre-project team for additional constraints on payload mass, volume, data rate, and configuration.

Charter-specified statement of task:

1. Determine the payload options and priorities associated with achieving science objectives A, B, and C. Recommend a mission concept that would maximize overall science return and progress towards NASA's long-range goals within the resource and risk posture constraints provided by HQ.
2. Determine the degree to which HEOMD measurements or STP technology infusion/demonstration activities (Objective D) can be accommodated as part of the mission (in priority order), consistent with a separate (from SMD) budget constraint also to be provided by HQ.
3. Work with the pre-project team in developing a feasible mission concept.
4. For the favored mission concept, propose high-level supporting capability requirements derived from the scientific objectives, including both baseline and threshold values.
5. Develop a Level 0 Science Traceability Matrix (similar to those required for SMD mission Announcements of Opportunity) that flows from overarching science goals/objectives to functional measurements and required capabilities for the surface mission in 2020.
6. Define the payload elements (including both instruments and support equipment) required to achieve the scientific objectives, including high-level measurement performance specifications and resource allocations sufficient to support a competitive, AO-based procurement process:
   - Provide a description of at least one "strawman" payload as an existence proof, including cost estimate
   - For both baseline and any threshold payloads, *describe priorities for scaling the mission concept either up or down (in cost and capability) and payload priority trades between instrumentation and various levels of sample encapsulation.*
7. Assess the potential value and cost for improving access to high-value science landing sites.

To carry out its assignment, the SDT broke the work down into three broad phases (see Figure 2-2).

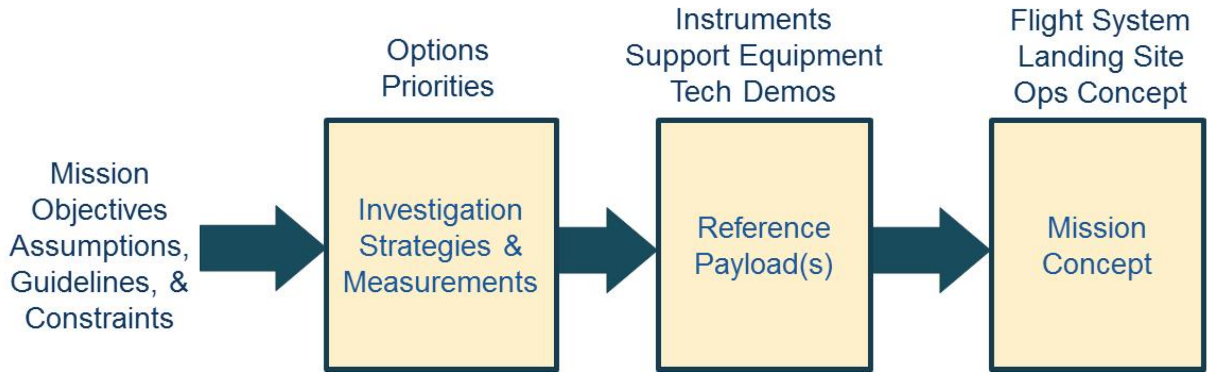


Figure 2-2. Roadmap showing the SDT process.

Phase I addressed definitions broadly described in the charter, and identified the priorities, measurement options and implementation possibilities specified in the first two tasks. The SDT divided into four subteams (Habitability, Biosignatures, Sample Return, and HEO/STP) with each subteam focusing on a different mission objective. Each team began by better defining and describing the scientific foundation for the different objectives through separate weekly teleconferences. Each subteam reported back to the full SDT at a series of weekly teleconferences and one two-day face-to-face meeting, culminating in the findings reported in Section 3 of this report. The results from Phase I were submitted to NASA in an interim progress report on April 1.

Phase II synthesized the work from Phase I into integrated reference payloads, including instruments, demonstrations, and scientific support equipment. These results are presented in Sections 5 and 6 of this report.

Phase III consisted of integrating all of the above into a mission concept, consisting of the kind of operations scenario needed to achieve the objectives, the nature of the landing site, and the design of a rover that could access the necessary landing site, carry out the necessary operations, and carry the payload that could do all of the above. Results are reported in Sections 7 through 9 of this report

As a practical matter, the SDT carried out Phases II and III concurrently. New subteams with different memberships than in Phase I were organized (Traceability Matrix, Payload Support, Payload Concept, Landing Site Access Considerations, Mission Concept – Integration, and Operations Concept). Each subteam reported back to the full SDT at a series of weekly teleconferences and at one two-day face-to-face meeting,

2.2 The Overall Context of the Objectives (why are they important, why now?)

2.2.1 Explore an Astrobiologically Relevant Ancient Environment (Objective A).

Among the most fundamental scientific objectives of any surface mission is to explore a site in a manner that significantly expands knowledge of the geologic processes and history of Mars beyond that available from orbit. The continuing successes and discoveries made by orbital missions have increased dramatically the breadth of knowledge of Mars. But observations made from the surface, especially those from a roving vehicle, are in some cases the only way to fully address questions related to, for example, the role and extent of water on Mars; the breadth of volcanic activity; the nature and diversity of habitable environments; and ultimately, the possibility of life. The Mars 2020 mission comes at a time when the benefits of rover exploration of Mars have been readily demonstrated and the potential to optimize a rover payload and exploration strategies could be fully realized. A rover so equipped and directed to explore an astrobiologically relevant ancient environment on Mars would be poised to deliver high-value *in situ* science as well as support for the other mission objectives.

2.2.2 Search for the Signs of Past Life (Objective B).

An ongoing key goal in space exploration is to determine whether life ever existed beyond Earth (Des Marais et al., 2008). Finding life elsewhere would have an enormous impact both scientifically and socially. There is a broad societal interest especially in areas such as achieving a deeper understanding of life, searching for extraterrestrial biospheres, and extending human presence to other worlds. Key questions include the following: If life ever arose elsewhere, could it be related to life on Earth or did other bodies in the solar system sustain independent origins of life? If life never developed elsewhere, could there be a prebiotic chemical record preserved in ancient rocks with clues about how life began on Earth? Mars is particularly compelling because Earth's climate has been more similar to Mars' than that of any other planet in our solar system. The search for evidence of life beyond Earth begins with the premise that biosignatures would be recognizable in the context of their planetary environments. A biosignature (a "definitive biosignature" or DBS) is an object, substance and/or pattern whose origin specifically requires a biological agent. The usefulness of a biosignature is determined not only by the probability of life creating it, but also by the improbability of non-biological processes producing it. Thus because a biological "signal" must be resolved from any non-biological environmental "noise," the search for evidence of life is closely tied to interdisciplinary investigations of planetary environments and their capacity to sustain life (MEPAG, 2010).

2.2.3 Progress towards Mars Sample Return (Objective C).

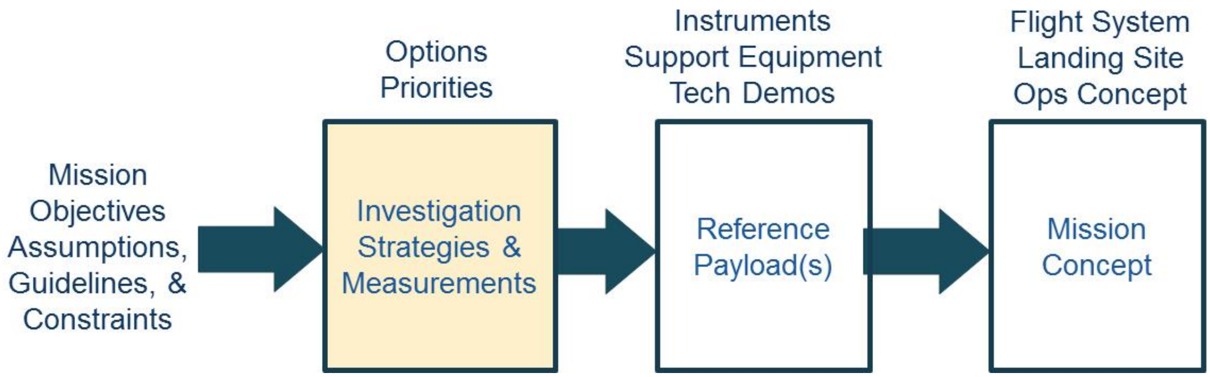
The proposed Mars 2020 rover mission, and the SDT's preparation for it, are a part of NASA's long-term goals for planetary exploration as described in the Decadal Survey report on Planetary Science (NRC, 2011). NASA accepted the Decadal Survey's highest recommendation for Mars exploration, which is of the return of selected samples from Mars to the Earth. "Therefore, the highest-priority missions for Mars in the coming decade are the elements of the Mars Sample Return campaign—the Mars Astrobiology Explorer-Cacher [MAX-C] to collect and cache samples, followed by the Mars Sample Return Lander and the Mars Sample Return Orbiter … to retrieve these samples and return them to Earth, where they will be analyzed in a Mars returned-sample-handling facility." (NRC, 2011; p. 164).

Mars 2020 would be intended to "… enable concrete progress toward sample return, thereby satisfying the NRC Planetary Decadal Survey science recommendations…." This plan would be consistent with that of the Decadal Survey's MAX-C concept: to seek out and identify materials from former habitable environments, to collect them, and to cache them on Mars for return to Earth by later spacecraft missions. Mars 2020 would not be MAX-C as envisioned in the Decadal Survey (NRC, 2011), in that Mars 2020 would be based on hardware designs of MSL rather than of MER, and would be able to accommodate HEOMD payload elements.

2.2.4 Opportunities for HEOMD/STMD Contributed Participation (Objective D).

NASA has a clearly stated agency-level desire to better integrate SMD, HEOMD, and STMD objectives across missions whenever possible. The Mars 2020 rover mission represents a major opportunity for such integration. Consideration of SMD, HEOMD, and STMD participation in Mars exploration missions was a major part of the Mars Program Planning Group (MPPG) effort in 2012, and it set the stage for the more specific consideration applied by this SDT. Several members of the MPPG continued their integrative efforts as formal and ex officio members of this SDT.

The SDT considered a wide variety of potential HEOMD and STMD contributions to the Mars 2020 rover mission—some were similar in context and structure to a science instrument and could be assessed accordingly; others were more integrated into the flight subsystem(s) and required a more specialized assessment with strong support from the flight system team. Furthermore, some proposed contributions were targeting increased performance for this mission (e.g., EDL landing accuracy improvements), while others were intended as data collection and/or technology demonstration opportunities that would benefit future missions (robotic or crewed). The SDT attempted to balance these varied implementation classes, temporal applicability, and mission directorate objectives to develop prioritized candidate contributions from HEOMD and STMD.



Current location in the "Roadmap"

3 Technical Analysis of Mission Objectives

3.1 Introduction to Key Concepts

The SDT divided into subteams that evaluated each of the four charter-specified objectives (Section 2.1) independently. In their initial deliberations, none of the subteams presumed an outcome for objectives other than the one on which each focused. However, once the evaluations of Objectives A, B, and C were each complete, and the SDT's priorities for achieving those objectives were documented, it became clear that there are important commonalities between requirements for meeting each objective. The data to be collected in order to achieve Objective A (determine habitability) also comprises most of the data required to address Objective B (search for biosignatures). Moreover, the investigations of Objectives A and B also provide the basis to select samples of key rock formations to address Objective C (demonstrate significant progress toward sample return). These relationships are illustrated in Figure 3-1.

In compiling this report, therefore, the SDT cannot present a cogent analysis of Objective A without alluding to its relationship to Objectives B and C, even though detailed discussion of the latter objectives is presented later. Likewise, analysis of Objective B would be incomplete without discussion of its linkage to Objective C.

Key Terminology Used in This Report

1. ***Astrobiologically relevant ancient environment*** An environment that appears to have once been capable of either supporting life as we know it or sustaining pre-biological processes leading to an origin of life.
2. ***Habitability*** The capacity of an environment to provide simultaneously the solvent (e.g., water), nutrients, energy and conditions needed to sustain life as we know it
3. ***Potential biosignature (PBS)*** An object, substance and/or pattern that might have a biological origin and thus compels investigators to gather more data before reaching a conclusion as to the presence or absence of life.
4. ***Biosignature Preservation Potential (BPP)*** The capacity of a given environment and the geological deposits it produces to preserve biosignatures.
5. ***Threshold:*** Measurement or capability levels below which a mission may not be worth the investment.
6. ***Baseline:*** Measurements or capabilities necessary to achieve the science objectives of the mission and a point of departure from where implementation begins.

Thus, to help the reader to navigate this report, we offer the following look ahead:

- The central element of our proposed approach to achieve Objective C (Section 3.4) would be the assembly of a returnable cache of martian rock and soil samples. No activity less than this provides progress toward sample return while not requiring repetition on a future mission, *and* sets the stage for far more sophisticated and comprehensive laboratory analyses (on Earth) than have been or can be completed *in situ*.
- The measurements needed to conduct *in situ* astrobiology investigations (Objective B) (Section 3.3) are essentially the same set that would support exploring for, identifying, and characterized the context of samples that would go into the cache.
- Finally, characterization of the field site and assessing its past habitability (Objective A; Section 3.2) is scientifically valuable in its own right, but also meets the majority of requirements for Objective B, and also meets requirements for both selecting and documenting the context of the samples for Objective C.

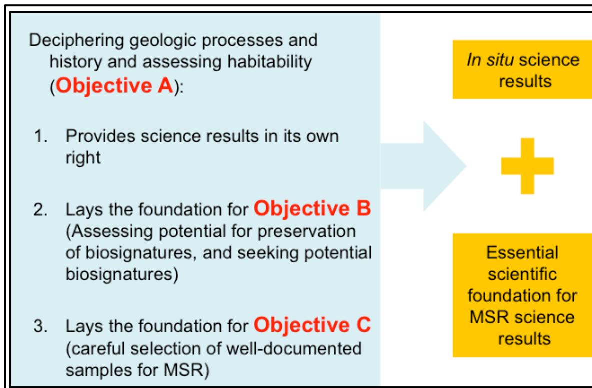


Figure 3-1. The processes of interpreting geologic processes/history, understanding habitability, evaluating potential biosignatures, and decision-making for sample caching are connected

Objective D is relatively independent of the three science objectives (A-C).

3.2 Objective A: Explore an Astrobiologically Relevant Ancient Environment on Mars to Decipher its Geological Processes and History, Including the Assessment of Past Habitability

3.2.1 Scientific Foundation

3.2.1.1 Introduction

The exploration of an astrobiologically relevant ancient environment for the 2020 mission would be driven by multiple objectives linked by the need to decipher the geological processes and history of the site. We interpret an "astrobiologically relevant ancient environment" as an environment that was once capable of either supporting life as we know it or sustaining pre-biological processes leading to an origin of life. Assessing past habitability requires knowledge of the geologic history of the site obtained from both orbital and ground observations. Of particular importance would be determining the environments and sequence in which the local rocks were emplaced and subsequently modified. Such an investigation would be necessary to support the goals of Objective B to understand the potential for biosignature preservation and to search for any biosignatures that may be preserved. This effort also would be crucial to Objective C, which involves selecting and documenting samples consistent with the science objectives and priorities for returned sample science as identified in recent reports of E2E-iSAG (2012), JSWG (2012), and MPPG (2012). There is significant synergy between all three objectives.

> *The Mars 2020 rover would…*
>
> *…provide major breakthroughs using a combination of measurements previously unavailable to understand ancient environments on Mars that may have once been abodes for life.*

Finding A-1: Deciphering and documenting the geology of the rover field site provides *in situ* science results. These results are required both for Mars 2020 mission *in situ* objectives and for subsequent returned sample science objectives

3.2.1.2 Deciphering Geological Processes and History

Objective A addresses the concept of "scientifically selected, well-documented" samples as described in Objective C. This requires acquisition of a range of geologic observations of a site with sufficient quantity and variety to allow confident tests of competing hypotheses about past environmental conditions and spatial-temporal relationships in the geologic record.

3.2.1.2.1 Quantity of Geologic Observations: Spirit Rover Example

E2E-iSAG (2012) used observations made by the rover Spirit to demonstrate what is required to well document a site with geological diversity, as would be desired for the 2020 mission. In its first Mars year of exploration, Spirit drove ~4 km from the lander to the Haskin Ridge outcrop called Seminole, guided in part by observations made from orbit. Using the average estimated rock abundance of 15% along a visibility band of 15 m on either side of the traverse path, roughly 20,000 rock targets were present. Among these, ~600 (including soils) were targeted by Spirit's color camera and infrared spectrometer, both to identify candidates for further investigation by the arm-mounted instruments and to provide context for the investigated targets. Roughly 100 targets were then analyzed by contact instruments. In the case of a sample caching mission, the SDT suggests that ~30 samples would then be collected. This example demonstrates both the winnowing process that would be needed to identify the most desirable samples and the large number of measurements necessary to understand the relationship between the samples and the site.

Finding A-2: To ensure that a site and the samples from it are well documented, the rover's tools and instruments must be capable of making a sufficient quantity, variety and quality of geologic observations to interpret past environmental conditions and to understand spatial and temporal relationships in the geologic record.

3.2.1.2.2 Variety of Geologic Observations: Importance of Multiple Scales

Mars rover field sites are selected on the basis of observations acquired from orbit, and exploration of a site is guided in part by these observations. On the ground, new observations are acquired at various overlapping spatial scales (Figure 3-2). Some of the ground observations, particularly images of the landscape all around the rover, are acquired at a scale that permits a comparison between landforms seen from the ground and those seen from orbit (e.g., Arvidson et al, 2008; Squyres et al., 2009). These observations help to locate the rover relative to features on maps, test hypotheses, and guide the decision-making process as to where to conduct detailed investigations.

Higher-resolution observations acquired using the rover's tools and instruments are placed within the context of the landscape panoramas and overhead views. Geologic maps constructed from these data are refined continuously as observations from the rover lead to new understanding and synthesis. Merger of the regional and local data provides not only a planimetric map view of the terrain the rover would investigate, but also the three-dimensional understanding of stratigraphic relationships between differing rock units. This further translates into an understanding of the temporal and facies[1] relationships (e.g., Grotzinger et al., 2005). The latter are the sub-environments captured in the rock record; for example, a stream environment gives way to a deltaic environment gives way to a near-shore sublacustrine or submarine environment.

[1] Facies – a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process

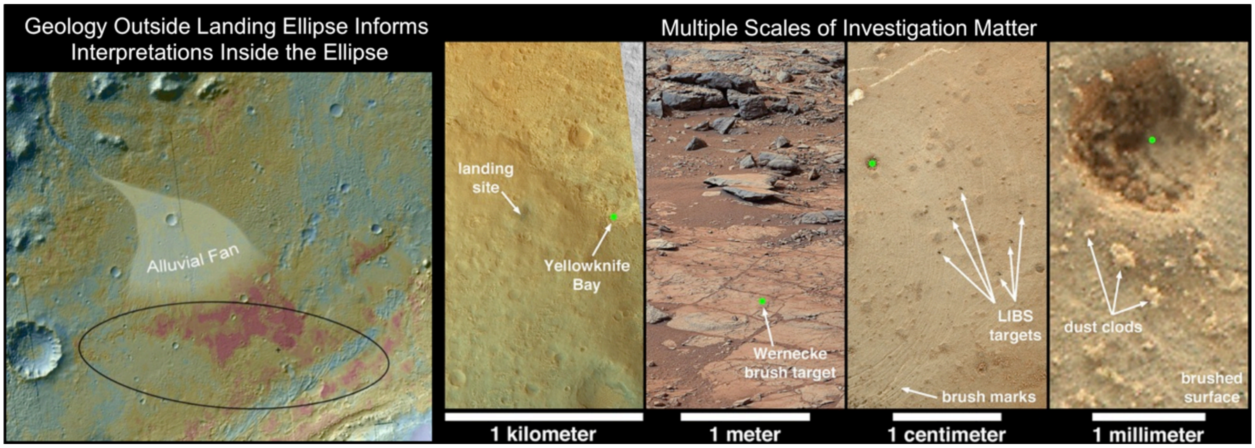


***Figure 3-2*. *Data with overlapping spatial scales are critical to interpreting the geology*.** *Nested views of the MSL landing area showing Mars sedimentary rocks at multiple scales. The green dot in each image is at the same location). Left: MRO-based digital elevation model of NW Gale Crater, and MSL landing ellipse. Colors map to thermal inertia (from THEMIS, on Mars Odyssey). Center Left: MRO HiRISE image of Curiosity's landing site; rover at Yellowknife Bay. Center: Mosaic of MSL Mastcam images in Yellowknife Bay. Mudstone rocks in foreground, sandstone ledge in background. Center Right: MSL MAHLI image of brushed rock target named Wernecke, showing chemical analysis spots of MSL ChemCam LIBS and brushmarks. Right: MSL MAHLI image of brushed surface; 16.5 µm/pixel view of Wernecke brushed target, showing a 'mini-bowl' at top, and dust clods formed during brushing event. Image credits: NASA/JPL-Caltech; Arizona State University-THEMIS; University of Arizona-HiRISE; and NASA/JPL-Caltech/Malin Space Science Systems - Mastcam and MAHLI.*

Interpretation of geologic records of past environments involves observing geologic features at mutually overlapping scales that range from synoptic to panoramic/landscape to the hand-lens or microscopic scale. Observation at multiple scales would be required to interpret the nature of past environments (e.g., subaerial, subaqueous; reducing, oxidizing) and events (e.g., tephra fall, lava flow, fault offset, vein-filled fracture) recorded in rock. Combining orbiter and rover panoramic to microscopic observations places all of the observations in context and reveals lateral as well as vertical relationships, permitting interpretations of the sequence of events and succession of environments in the record.

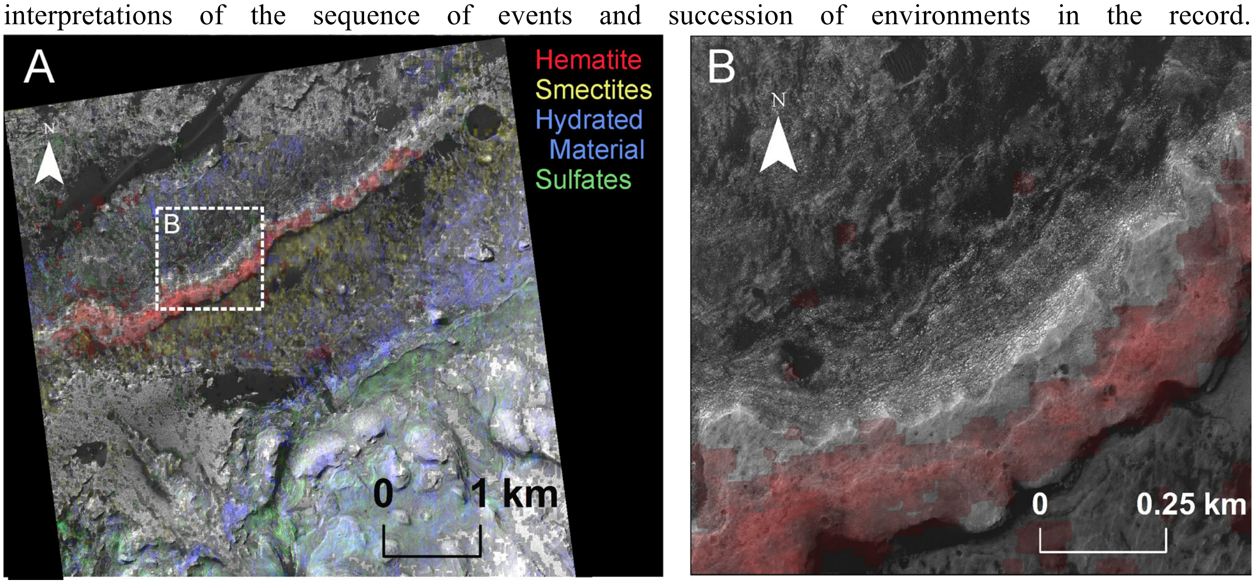


Figure 3-3*. *Connecting orbital data with rover-scale data improves the geologic interpretation. *Mars Reconnaissance Orbiter of Mount Sharp strata planned for Curiosity rover traverse. Grayscale represents 30 cm/pixel HiRISE images, and color shows minerals from CRISM images. (A) Northwest flank of Mount Sharp, with elevation increasing from upper left to lower right. (B) Mineral occurrence and morphology at rover traverse scale enables planning of traverses and for possible contact measurements. From Fraeman et al (2013), submitted.*

Finding A-3: Rover imaging and compositional observations should be of sufficient coverage, scale and fidelity to permit their placement into the context of orbital observations.

The important relationship between orbital and landed observations is clearly demonstrated by the Mars Science Laboratory site in Gale crater. High spatial resolution data from the Mars Reconnaissance Orbiter (MRO) were instrumental in the assessment of the site's past habitability based on interpretations of morphological and mineralogical indicators of past aqueous processes (Fig. 3-3) (e.g., Milliken, 2010; Thomson et al., 2011). In addition to providing context for the landed measurements, the orbital data allowed formulation of a detailed strategic plan for the rover investigation. The plan involved exploration and sampling of the various stratified deposits of Mount Sharp that have compositions suggestive of diverse paleoenvironments.

Finding A-4: Orbital observations are essential for establishing geological context and for identifying and mapping the different rock units that represent a diversity of paleoenvironments.

3.2.1.3 Assessment of Past Habitability

A major focus of Objective A is the assessment of past habitability in an identified astrobiologically relevant ancient environment. Here we describe various aspects necessary for this assessment.

3.2.1.3.1 Requirements of Habitability

From knowledge of terrestrial habitable environments, at least four broad factors can be identified as necessary for habitability: 1) Water (a solvent), 2) Raw materials, 3) Energy, and 4) Favorable conditions (Fig. 3-4) (Hoehler, 2007). We assume that the same factors apply to Mars and that assessing martian habitability involves identifying and, where possible, quantifying these factors in the geologic record at the rover's field area.

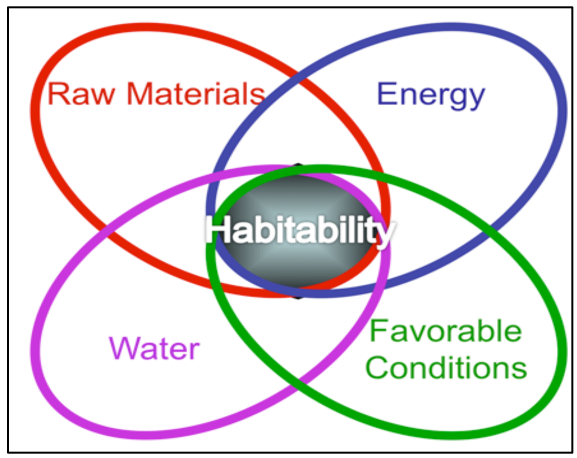


Figure 3-4. A habitable environment must have water, raw materials, energy, and favorable conditions*. A habitable environment is possible only where and when four broad requirements are simultaneously attained: availability of raw materials (elements and chemical compounds); availability of free energy in sufficient abundance and adequate form; availability of liquid water (a solvent, catalyst, and source of energy in some environments); and favorable conditions, including stability, protection from ionizing radiation, and mechanical energy of the environment (adapted from Hoehler, 2007).*

Habitability occurs at the intersection of these factors, which need to be sought on Mars. Water is now understood to be an important geologic agent on Mars, more so in the distant past than in the present. To assess its role in providing habitable conditions requires an understanding of both the amount of water present and its persistence in a given place and time. The raw materials necessary for life include the so-called CHNOPS elements and a source of electron donors. Their availability in the geologic environment (beyond those species present in the atmosphere) needs to be investigated. The same is true for energy sources and their availability, for example: mineral suites of mixed valence states for redox energy; proximity to a paleosurface to enable photosynthesis; and radiogenic elements for radiolysis. Lastly, favorable conditions include: the properties of available water like salinity, pH, and temperature; the energy of water in the environment (e.g., quiet vs. energetic), which has implications for the stabilization of microbial communities; protection from radiation like that provided by a planetary dipole field; and the rate of burial, for example, in a lacustrine setting, which has implications for the viability and stability of microbial communities.

3.2.1.3.2 Habitability in the Geologic Record

Although the basic characteristics of a habitable environment are largely understood and can be measured directly in present-day environments, understanding the habitability of past environments relies on interpretation of indirect and incomplete evidence in the geologic record (Fig. 3-5). As an environment is preserved in the rock record, evidence of some of the aspects that made it habitable may be lost altogether. For example, organic carbon that was an energy source in a paleoenvironment may be entirely absent in the geologic record due to degradation.

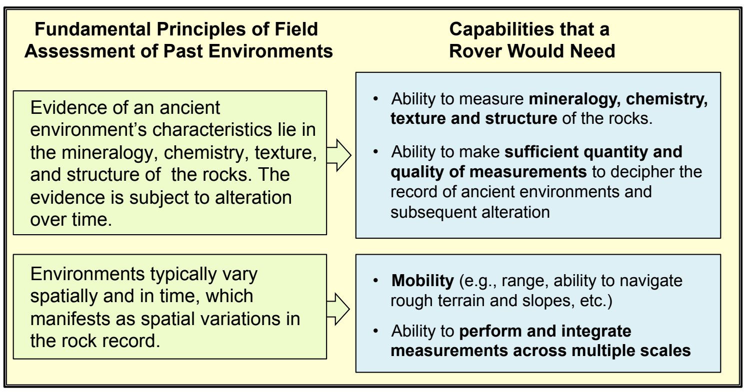


Figure 3-5. To interpret a geologic environment, it is important to have a mobile rover with a long life span and instruments that can take data on mineralogy, chemistry and texture.

Aspects of the environment that do become part of the geologic record typically are recorded by means of physical and chemical proxies. For example, evidence of surface water may be recorded in sedimentary structures and bedding architecture, whereas direct evidence of water (interstitial or mineral-bound) may not necessarily be preserved, or even if preserved, may not be related to the original surface body of water or reveal many of its characteristics. Evidence of "favorable conditions" may be found in a host of proxy information. For example, water salinity may be recorded by precipitated mineral assemblages; water temperature may be recorded in stable isotope composition of precipitated minerals or in sedimentary structures that indicate ice rather than liquid water. Water depth may be indicated by the characteristics of ripple marks or by signs of desiccation. The longevity of subaqueous conditions may be indicated by a combination of sedimentary structures and bedding characteristics.

Accordingly, past habitability is assessed in the geologic record largely by examining proxies, and much less by examining evidence for habitability criteria directly. Thus, a rover equipped to investigate diverse aspects of past habitability needs to be capable of examining rock textures and structures, mineralogy and chemical variations, bedding characteristics, and so forth. In addition, more detailed aspects of habitability could be measured through analysis of returned samples (e.g. micro-scale stable isotope variations or fluid inclusion analyses), and a sample-collecting rover would need to be able to identify materials suitable for such analyses.

Finding A-5: Some records of habitability may not be preserved or detectable. **Thus, inability to detect geologic evidence for all four habitability factors does not preclude interpretation of a site as a past habitable environment.** A key strategy for interpreting past habitability is to seek geochemical or geological proxies for past conditions, as recorded in the chemistry, mineralogy, texture, and morphology of rocks.

3.2.1.3.3 Habitability and its Potential for Preservation

There are two important aspects to consider when evaluating the habitability of past environments at a site. First, rock strata may record multiple past environments that existed together at any given time. Exactly how many environments existed at one time depends on the scale of observation. For example, at a regional scale an entire deltaic system may be viewed as a single paleoenvironment, or it may be subdivided into a deep water distal facies that is a different paleoenvironment from the proximal upper delta, or the trough of a ripple is a different paleoenvironment compared to the ripple crest. It is important to observe the environmental variations across a broad range of scales in order to fully understand past habitability, as each piece could provide critical constraints on the reconstructed geological and environmental history.

Second, the rocks may record multiple events or changing sets of conditions through time since they were first formed. Where this occurs, it is absolutely critical to correctly understand the relative timing of different conditions that are relevant for understanding habitability. For example, if hydrated minerals are associated with a body of rocks that crosscuts bedded stratigraphy, then those hydrated minerals do not imply an aqueous environment during the deposition of those beds. To make these kinds of observations, it would be crucial that a rover has the ability to map out cross-cutting and stratigraphic relationships.

> **Major Finding A-6:** Assessing habitability and preservation potential at a site with a record of multiple paleoenvironments requires a rover that can navigate the terrain to conduct lateral and stratigraphic surveys in order to analyze a range of targets at multiple spatial scales.

3.2.1.3.4 Other Types of Geologic Observations

Although assessing habitability is a major focus of Objective A, deciphering the geological processes and history of the rover's field area entail a range of observations not necessarily directly indicative of habitability. Full details of the required observations at a particular outcrop cannot be predicted precisely. However, the *types* of observations that are likely to be critical are well understood and can be considered for two broad rock classes: those involving the role of water, as with aqueous sediments and hydrothermally altered rocks, and those involving igneous processes. The E2E-iSAG (2012) report presented various observations related to both classes of rocks, as shown below (Fig. 3-6).

Relevant Features When Interpreting Water-laid or Water-altered Rocks

- Lateral/vertical changes in a sedimentary deposit or hydrothermal sediments
- Physical variations in a mineral phase: texture, crystal habit, or residence in veins/ layers/ cement/ clasts / concretions
- Inferred salinity gradient in a saline mineral assemblage
- Variations in detectable organic matter: host mineralogy, concentration, spatial arrangement
- Sedimentary structures and textures, associated mineralogical variations
- Mineral transition across a zone of alteration
- Sequence of vein-fill deposits
- Proximal-distal trends at a hydrothermal vent

Relevant Features When Interpreting Unaltered Igneous Rock

- Petrologic character: ultramafic to granitic, mineralogic, trace element properties
- Age
- Type and intensity of aqueous alteration [if they are unaltered (see above) this bullet is not relevant]
- Type of occurrence: outcrop, "subcrop," or float
- Igneous setting: intrusive, extrusive
- Grain size, chemical variation in minerals
- Degree of weathering
- Degree of impact shock metamorphism, including brecciation

Figure 3-6. Rocks from both sedimentary and igneous settings are necessary to bring back to Earth. *Investigating both is required to interpret a geologic record and both are candidates for sampling (modified after E2E-iSAG, 2012).*

3.2.2 Measurement Options and Priorities

3.2.2.1 Science Objectives Flow to Measurement Types

As presented in previous sections, Objective A includes various intermediate objectives and associated observations from Findings A-2, A-3, A-5 and A-6. The minimum suite of measurements required to address Objective A then flows from these observations. Figure 3-7 graphically depicts this flow.

An example, for illustrative purposes only, is as follows:

- Mission Scientific Objective:
  Assess past habitability and potential preservation of possible biosignatures.
- Intermediate Objective:
  Seek geologic materials in which biosignature preservation potential may be high.
- Observation Needed:
  Identify a candidate mudstone by distinguishing very fine sand from silt in a sedimentary rock.
- Measurement:
  Fine-scale imaging.
- Functional Requirement:
  Resolve grains < 62.5 µm in size (smaller would be desirable).

Figure 3-7. Traceability Matrix "road map." *The minimum suite of measurements necessary to address the mission objectives must flow from those objectives in the manner shown.*

The SDT thus focused on the flow-down from Mission Science Objectives to Measurement in order to identify the threshold (minimum) and baseline (desired) suite of measurements needed to address Objective A. These *in situ* measurements also were regarded as vital to supporting aspects of Objectives B and C.

In considering the threshold and baseline measurements, the SDT endeavored to describe them in accommodation-neutral terms. For example, panoramic imaging of the landscape is a measurement that the MER and MSL rovers performed by mast-mounted cameras. The description of mast-mounting of these cameras concerns accommodation; the SDT avoided this form of statement so as not to preclude options for alternative accommodations. The SDT envisions, for example, that there are numerous accommodations, or mounting positions, on a rover that would provide opportunities to observe geologic materials in the rover's robotic arm workspace.

3.2.2.1.1 Improved Spatial Focus and Correlated Datasets

One of the breakthroughs of the MER mission was the ability to resolve structural and textural features in rocks and soils at the sub-millimeter scale via an optical instrument (the Microscopic Imager, or MI), which allowed for improvements in interpreting the origin and history of these materials in a manner akin to that provided by a geologists hand lens. A compelling example is the ability to fully resolve and characterize the morphology of the hematite spherules at Meridiani Planum. But the associated chemistry and mineralogy measurements were applied at scales one to two orders of magnitude larger. For example, elemental chemistry data from the APXS instrument are acquired at a spatial scale of roughly two centimeters. Even the color imaging via Pancam cannot fully resolve the same features evident in the MI views. Such scale mismatches tend to hinder critical interpretations of fine-scale features. At Meridiani Planum, definitive correlation of hematite mineralogy with the spherules was significantly encumbered by scale mismatches between the Mössbauer/Mini-TES spectrometers and MI observations, slowing the interpretation of their origin.

Instruments on board the rover Curiosity demonstrate some advances that would benefit the 2020 mission. MAHLI combines color and fine-scale imaging in one instrument. ChemCam allows elemental chemistry to be measured at spots comparable to the resolution of MAHLI. Together, these instruments point the way to measurement scale-improvements that are highly desirable and responsive to the 2020 mission objectives.

The next leap in our ability to interpret the origin and evolution of rocks will come with the capability to combine mineralogy, texture, and ideally, chemistry observations at a scale comparable to that of the grains within rocks. This is the essence of a sub-discipline of geology known as petrology, which concerns the origin and evolution of rocks. Some observations possible at the grain scale that constitute critical petrologic input include the nature of the rock's component minerals or grains, and cross-cutting or overgrowth relationships that give an indication of how the rock has changed with time. The instruments necessary to make measurements at this scale now exist, and the SDT assumes they would be proposed to the Mars 2020 mission.

Some examples of possible petrologic observations are illustrated in Figure 3-8. Importantly, measurements of this kind benefit from a smoothed surface for which the technology has been well established by MER. Using the principles of petrologic analysis would be especially powerful for the scientific objectives of the proposed mission. Interpreting habitability, the preservation of the evidence of that habitability, the potential for preservation of biosignatures (see Section 3.3) and the search for biosignatures (Section 3.3) all are either significantly enabled by, or are completely dependent upon, these fine-scale, co-registered observations.

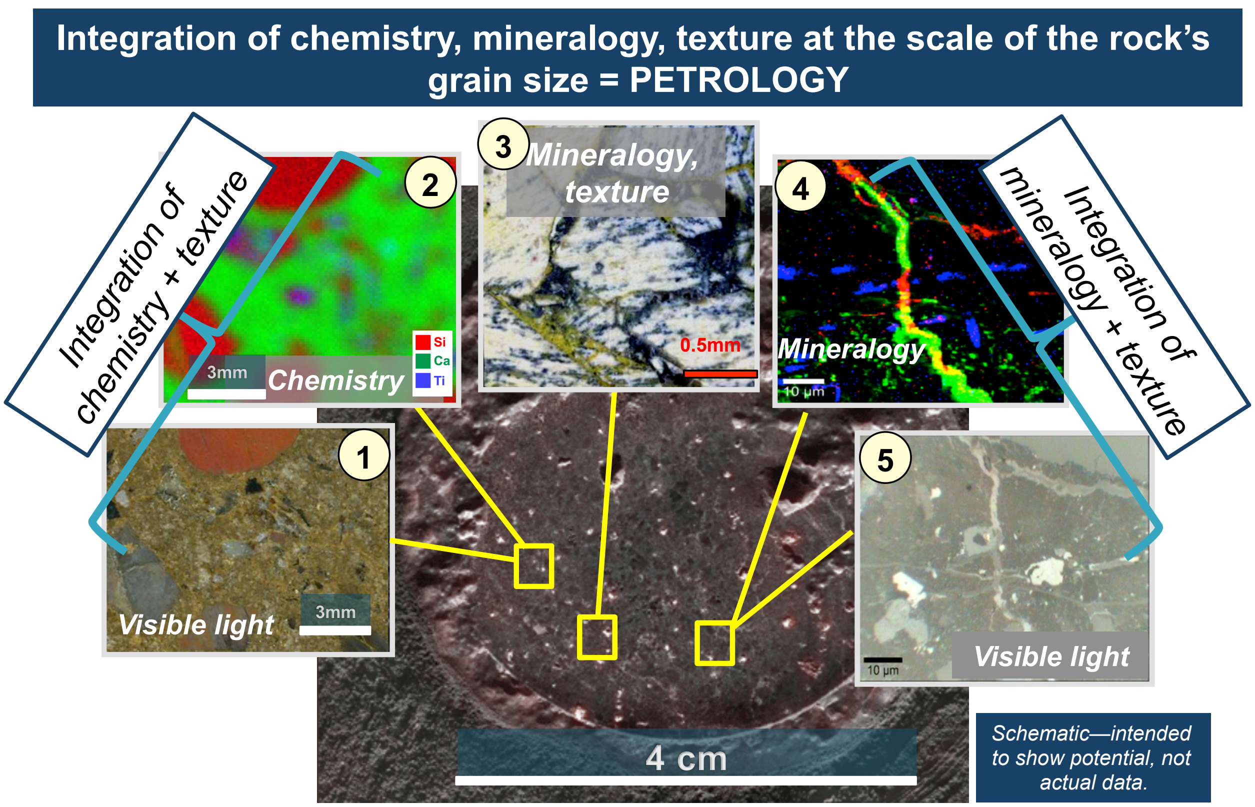


***Figure 3-8. Schematic illustration of the potential use of fine-scale observations of an abraded surface to collect petrologic data**. Base image is MI/Pancam merged images of a ground and brushed RAT hole (~45 mm diam.) in the rock Humphrey at the Spirit site. Inset images (from left to right): 1). Visible light image of a terrestrial conglomerate; 2). Hyperspectral element map of the same rock as #1 with the Micro-XRF instrument. Red = Silicon, Green = Calcium, Blue = Titanium. Courtesy A. Allwood; 3). Mineral map using near-IR spectroscopy. False-color RGB composite 1.43, 1.05, 0.74 µm showing mineral variations. Courtesy J. Farmer; 4). Mineral map of a Mars meteorite with green Raman: Red = jarosite, Green = goethite, Blue = clay minerals. Courtesy M. Fries; 5). Visible light image of #4.*

Finding A-7: The ability to correlate variations spatially in rock composition with fine scale structures and textures is critical for geological and astrobiological interpretations.

3.2.2.2 Implementation Options for Objective A

Seventeen different categories of measurements were identified from two community workshops and other literature (see Appendix 4) and evaluated for responsiveness to all objectives of the Mars 2020 mission. These are shown below without prioritization.

- Contact mineralogy
- Elemental chemistry
- Context mineralogy
- Contact organic detection/characterization
- Organic characterization in processed samples
- Redox species from processed samples
- Geochronology
- Radiation environment
- Meteorology
- Context imaging
- Microscopic imaging
- Atmospheric trace gas detection
- Stable isotopic ratios
- Mineralogy in processed samples
- Subsurface characterization
- Remnant magnetic properties
- Regolith/dust properties

To assess the applicability of these 17 categories to the mission objectives, a Science Traceability Matrix was created (Table 3-1). This matrix was constructed around the idea that the minimum suite of measurements required to address Objective A must flow from the objectives discussed in Section 3.1. This flow within the matrix is graphically depicted in Figure 3-7.

Five types of measurements distinguished themselves by their relevance to most of the observations needed to address scientific objectives associated with investigating geology and habitability. These five were thus identified as the threshold requirements for achieving the objectives:

1. context imaging,
2. context mineralogy,
3. fine-scale imaging,
4. fine-scale mineralogy
5. fine-scale chemistry.

These five measurement types are necessary for making the kinds of basic geological measurements needed to document and interpret the geologic record of a site. At any site, there are minerals, chemical elements and visual features to observe and measure, and these features are the primary source of clues needed to interpret past environments and their habitability. Also the information provided by the different measurements can be both unique and complementary. For example, imaging using a few wavelengths shows spatial relations but provides only limited compositional information. Elemental abundances record many processes but do not by themselves provide a complete record of them. An example is the alteration of an igneous rock by water, where new phases are produced without significant transport of soluble elements. Such a process would be most strongly indicated by measurements of mineralogy.

“Context scale” is intended to mean measurements of the geologic content of the landscape around the rover, such as the characteristics of a large rock outcrop many meters from the rover. “Fine scale” is intended to mean measurements of smaller targets and more detailed analysis of features, such as mineral grains or textural features in materials found in the workspace of the rover’s robotic arm.

The baseline mission would include an option for up to two additional types of measurements: subsurface sensing and organic detection. As described below, these could provide additional information most useful in addressing the habitability and geologic history of a site. Other measurements would also be valuable, but due to their more limited mapping to the objectives of determining past habitability, they were not identified as part of the baseline.

Finding A-8: Five measurement types are threshold requirements to effectively and efficiently characterize the geology of a site, assess habitability, select samples, and document sample context: 1) context imaging and 2) context mineralogy, and, within the rover arm work volume, 3) fine-scale imaging, 4) fine-scale mineralogy, and 5) elemental chemistry.

The addition of organic matter detection would enhance the assessment of past habitability. Similarly, sensing of shallow subsurface composition or structure to facilitate and extend knowledge of setting and context and provide guidance to selection of samples for interrogation and caching would be highly desirable to help accomplish these objectives.

3.2.2.3 Measurement descriptions.

Following is a brief description of the required capabilities of each of the five threshold measurements. In each case, there must be a foundation for accurate conversion of raw data to physical units (e.g., geometrically corrected images, spectral radiance) on a rapid enough timescale not to impede tactical planning of rover operations based on analysis of the data.

<u>Context Imaging.</u> This measurement needs to image the terrain at a sufficient level of detail for navigational purposes (enabling the rover to travel at the required minimum distances per day), to characterize the geological context, to select at a distance locations for further in-depth analyses by close-up instruments and sampling, and finally characterize and help to validate the success of close-up investigations and sampling. For geologic interpretation at distance, both panoramic capability and resolution at range are necessary. For an outcrop being interrogated, resolution of small structures including large grains would be necessary. The threshold and baseline capabilities for achieving these observations are described in Table 3-1. Threshold capabilities would be satisfied by operation at an elevation +20° to -75°, and resolving a 1 mm feature at 2 m, or a 40 cm feature at 1 km. (Note: resolution is stated in the optical sense, i.e., satisfying a modulation transfer function or similar criterion.) A basic multispectral capability to distinguish unweathered from weathered material would be so useful as to be essential. This requires multiple bandpasses at 0.4-1.0 µm, on the ferric iron "red edge"; various combinations of filters each could have geologic merit. The most important capability for navigational purposes would be to support generating a DEM of sufficient accuracy and resolution for hazard recognition and planning the deployment of close-up payload. For deployment devices comparable to the MER or MSL arm, range resolution 1 mm at 2 m, or 2 cm at 10 m distance using stereo or other methods has proven adequate. Finally, to support expected operational timelines, the investigation should have operational and data management capabilities to support acquisition of a monochrome panorama and downlink it in ≤2 sols consistent with other operational constraints.

<u>Context Mineralogy.</u> This measurement serves a dual role in supplying actionable reconnaissance information for possible drive targets and for providing context for fine-scale measurements obtained within the rover's arm work volume. It also complements context imaging by detecting minerals at a distance that multispectral, extended visible-wavelength imaging does not distinguish. Identifying from afar the presence of key mineral phases in surface targets supports the selection of specific outcrops, rocks, and soils to investigate in detail with other rover instrumentation. It also allows mineral phases recognized within the work volume to be better understood based on their occurrence and distribution beyond the reach of the arm-mounted instruments. To achieve these objectives,, the instrument would need to be capable of acquiring remote rock and soil measurements with sufficient resolution to identify, at a minimum, the signatures (e.g., spectral absorptions or emissions, if spectroscopic techniques were employed) of the main igneous rock-forming minerals, as well as minerals indicative of past persistent liquid water including carbonates, phyllosilicates, sulfates, zeolites, and silica. Key requirements would be to detect occurrences of these classes of minerals 10 cm in size or greater, from a range of up to 10 m.

Beyond these threshold capabilities, desirable baseline capabilities would be to provide enhanced information on the presence, types, and distribution of key minerals. Detection of smaller occurrences, ~1 cm or less in size, at ranges greater than 10 m, would be valuable. It also would be valuable to detect mineralogical differences within these mineral groups resulting from differences in crystal structure, cation composition, and/or hydration state, and to detect halide minerals. In order to fit within tactical operation timelines, data needed to guide possible rover drive decisions would have to be of sufficiently small data volume to fit within available downlink resources for a given planning cycle.

Fine-scale Imaging. The objectives of this measurement are to characterize grain morphology and the textural fabric of rocks and soils at a microscopic scale. Data from this investigation: 1) would contribute to the characterization of the rover site's geological environment; 2) would illuminate details of local geologic history, such as crystallization of igneous rocks, deposition and diagenesis of sedimentary rocks, and weathering and erosion; and 3) may assist in the search for morphological biosignatures if preserved in the rock record. The microscopic imager would be tasked with obtaining information on shapes and textures of mineral grains or clasts, the nature of rock fabrics, and inter-granular color variations that could help to constrain textural relations among different mineral phases.

- Threshold requirements for the microscopic imaging instrument would be to acquire in-focus color images that resolve grains having the diameter of fine sand (62 μm) or smaller (at determined from satisfying a modulation transfer function or similar criterion). In order to survey an adequately large area to understand spatial relations, the footprint of the field-of-view at the working distance should be 2x2 cm or larger. Color capabilities require multiple bandpasses at 0.4-1.0 μm, on the ferric iron "red edge"; various combinations of filters each could have geologic merit. It is anticipated that, due to the uneven nature of surfaces to be imaged, autofocus or image stacking and processing may be required. Any autofocus capability should be internal to the imager and not require arm articulation.

Fine-scale Mineralogy. The objectives of this investigation are to detect and to measure the spatial distribution, at sub-millimeter scale, of the signatures of key minerals in outcrops, rocks, and soils. For objective B, a key purpose of the mineralogical measurement would be to detect potential biominerals, and to determine the mineral composition of other potential biosignatures and associated materials. As with the context remote mineralogy instrument, the mineral classes of interest are the main igneous rock-forming minerals, as well as minerals indicative of past persistent liquid water including zeolites, carbonates, phyllosilicates, sulfates, and silica.

- Threshold requirements would be to measure occurrences of these classes of minerals in features as small as 0.5 mm.
- Baseline capabilities are to detect occurrences of minerals of interest to ≤0.1 mm in size; to detect mineralogical differences within these minerals groups that result from cation composition and/or hydration state; and to detect halide minerals.

Fine-scale Elemental Chemistry. The objective of this investigation is to measure the abundances of major and selected minor elements most diagnostic of igneous, alteration, and sedimentary processes. Among the science goals of these measurements are to determine the fine scale elemental chemistry of sedimentary, igneous and diagenetic alteration features; to detect chemical evidence for mobilization of elements by liquid water, for example involving leaching or injection of hydrothermal fluids; to detect

Table 3-1. *Traceability Matrix for Objective A.*

Science Traceability for In Situ Investigations for Objective A: Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including assessment of past habitability

Habitability criterion	Science Goal	Science Objective	Measurement Objective	Relevant *In Situ* Investigations and What Performance Requirements are Driven by Measurement Objectives								Science support
				context imaging	context mineralogy	fine-scale imaging of arm work vol.	fine-scale mineralogy of arm work vol.	elemental chemistry of arm work vol.	organic detection, characterization in arm work vol.	subsurface composition	subsurface structure	rock surface dust/rind removal
Determine availability of water	Determine the amount of water that was present in the past	Sedimentary environment of deposition	3-D structure of sedimentary beds	footprint, detectability	footprint, distances	footprint	footprint	footprint, resolution			footprint, resolution	
			Elemental and mineralogic composition of sediments, diagenetic features		detectability	bandpasses	detectability, resolution	detectability		detectability		
			Sedimentary texture including grain-scale mineralogy, chemistry of rock components	resolution	resolution	resolution	resolution	resolution				
			Lateral and vertical variations within unit	bandpasses	quality	bandpasses	quality	quality		resolution	resolution	
		Conditions, processes and timing of <u>subsurface</u> aqueous alteration (hydrothermal, low temperature)	Morphologic, geometric evidence for fluid migration	resolution							detectability	
			Morphology, composition of alteration and diagenetic textures	resolution, bandpasses	resolution, detectability	resolution	detectability, resolution	footprint, resolution	resolution detectability		resolution	
			Nature of contacts at alteration front	resolution	resolution, detectability	resolution	detectability, resolution	footprint, resolution		detectability, resolution	detectability, resolution	
			Elemental and mineralogic composition and compositional variation within zones of alteration	bandpasses	detectability, quality	bandpasses	quality	detectability, quality	detectability, resolution	detectability, resolution		
	Determine how long aqueous conditions existed	Duration of (sub)aqueous sedimentary paleoenvironment	Thickness, lateral extent of aqueous/subaqueous deposits, signs of subaerial exposure	footprint, detectability	footprint	bandpasses	quality	detectability, quality		detectability, resolution	footprint, resolution	
		Timing and duration of subsurface aqueous alteration	Mineral assemblages that constrain chemical reactions	bandpasses	detectability	bandpasses	resolution, detectability	resolution, detectability	resolution, detectability			
			Cross-cutting relations of altered and unaltered material	resolution, bandpasses	resolution, detectability	footprint, bandpasses	footprint, detectability					
Assess presence of favorable environmental conditions	Determine water properties	Water temperature	Sedimentary structures and mophologic features indicative of drying, freezing, etc.	resolution	resolution	footprint	footprint					
			Identity and character of mineral indicators of temperature regime	bandpasses	detectability, resolution	bandpasses	resolution, detectability					
		Salinity	Saline mineral assemblages		detectability		resolution, detectability					
			Anion types and abundances					detectability, quality		detectability		
		pH	pH sensitive mineral assemblages and trace element chemistry		detectability, quality		resolution, detectability	detectability, quality				
	Determine conditions adverse to persistence of life	Water (wave) energy in the paleoenvironment	Sedimentary bedforms	resolution		footprint, resolution					footprint, resolution	
		Sedimentation rate	Texture and 3-D structure of sedimentary units			footprint					resolution	
		Ionizing radiation	Presence of a paleomagnetic field									
Assess availability of key elements and an energy source	Determine availability of key elements	Elemental abundance of CHNOPS	H, C, N, P and S concentrations and their distribution	bandpasses	detectability, resolution	bandpasses, resolution	resolution, detectability	detectability, quality	detectability, resolution	detectability, resolution		
			Mineral phases containing H, C, N, P and S		detectability		detectability	resolution, detectability				
	Determine availability of electron donors and acceptors to support metabolism	Availability of electron donors including organic C	Mineral phases containing mixed valence elements		detectability		detectability	detectability				
			Organic C				detectability, resolution		detectability, resolution			
			Mineralogy of unaltered rocks	bandpasses	detectability	bandpasses	detectability	detectability, quality		detectability		
	Determine if conditions could have supported photosynthesis	Habitable environments with access to sunlight	Sedimentological evidence for water environment exposed to sunlight	footprint, resolution	footprint, resolution	footprint, resolution	resolution					
			Texture and chemistry consistent with cryptoendoliths	resolution, bandpasses	resolution, detectability	bandpasses, resolution	detectability, resolution	resolution, detectability	detectability, resolution			
	Assess radiolysis as an energy source	Availability of radioactive elements	U, Th and K content of rock unit					quality, detectability		detectability		

compositional partitioning among phases, and (for objective B) to detect potential chemical biosignatures, and determine the elemental composition of other potential biosignatures.

- Threshold requirements would be to detect Si, Al, Fe, Mg, and Ca, with precision of ±10% if present at >1000 ppm, over spatial samples no larger than 2 cm, and K, P, S, Cl, Ti, Cr, and Mn if present at >100 ppm
- Baseline requirements would be spatial resolution of 0.1 mm.

In addition, the five threshold investigations described above should be complemented by a baseline organic detection investigation, both to provide contextual information on habitability and potential biosignatures, and to select if possible samples with preserved organic chemistry (see Finding A-8).

Organic Matter Detection. Organic matter detection provides valuable observations for assessing the processes that influence preservation of information about ancient environments. Preserved organic matter indicates an environment where complete oxidation of organic matter to CO_2 by abiotic processes has not occurred. Detection of organic matter can be used to help characterize meteoritic inputs, hydrothermal processes, atmospheric processes and other potential processes that might form abiotic (pre-biotic?) organic matter. Lastly, in order to identify the most desirable samples for possible return to Earth, detecting organic matter at a site has obvious value. The specific threshold and baseline requirements for organic matter detection are provided in Sections 3.3.1.4.4 and 3.3.1.4.5.

Subsurface Sensing. A significant challenge in Mars rover missions is the lack of access to vertical stratigraphy. In horizontal, nearly flat lying sedimentary rocks, a traversing rover would acquire limited knowledge of vertical stratigraphy including lateral variations in thickness of beds, pinching out, or lenses of different units. For example, Opportunity spent many months between contacts as it traversed the onlap of sulfate-bearing deposits onto Noachian terrain (Fig. 3-9, left). If subsurface sensing techniques that reveal these layers and their juxtaposition had been available, subsurface structure could have been correlated with local outcrops and traced laterally, providing a broader knowledge of stratigraphy years earlier than was achieved. Techniques that sense subsurface structural continuity could provide contextual information complementary to that obtained by the envisaged threshold payload for surface exposures. To provide information beyond that likely to be contained in orbital imaging from existing assets (e.g., HiRISE), smaller features than detectable from orbit must be resolved. Relevant horizontal and vertical scales of resolution are thus less than the ~30 cm scale provided by HiRISE. Ground-penetrating radar and electromagnetic sounding are examples of relevant techniques that could provide information to better understand local stratigraphy.

Another major challenge in rover exploration is the pervasive mantling of local bedrock by regolith and dust that has been laterally transported and in many cases homogenized. Most techniques for determining mineralogic or elemental composition, either contextually or at fine scale, penetrate only microns to millimeters into local rock or soil. Rocks and soils indicative of environments relevant to habitability (for example silica-rich deposits in the region of Home Plate explored by Spirit, Fig. 3-9, right) could be hidden from detection by centimeters of regolith or even microns of dust. The deposits at Home Plate were recognized in part because a faulty rover wheel created a narrow trench and exposed subsurface properties. A more planned capability to "see" through obscuring dust and regolith could enable discovery of material rich in phases formed in aqueous environments, thus benefiting the search for evidence of past habitability, some of which may be of sufficiently high priority to warrant caching of samples. High priorities for detection are minerals and elements commonly enriched in aqueous deposits, that pinpoint locations for further exploration. Major minerals and elements include sulfates (S), silica (Si), carbonates (C), or hydrated minerals (H). The relevant enrichments depend on the mineral or element; for minor ones like sulfates (S), carbonates (C), and bound water (H), a factor of two should be sufficient; better sensitivity is appropriate for silica (Si). Depth of penetration should be much greater than that obtained by surface preparation or by disturbance of soils by rover wheels, i.e. >>1 cm. Technologies to accomplish this measurement exist: for example, gamma ray techniques sense the key elements, at depths to >5 cm.

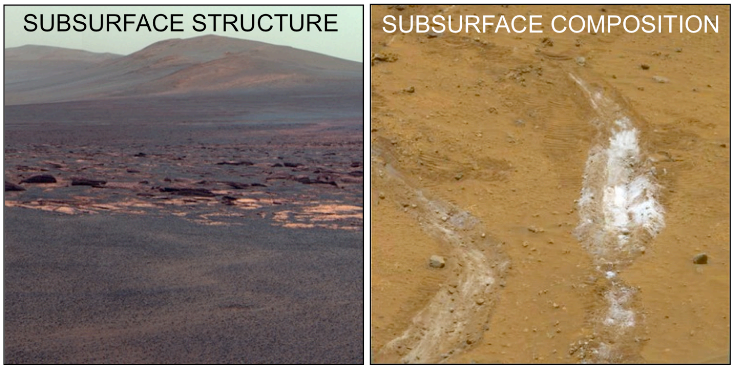


***Figure 3-9. Subsurface sensing would enable mineralogic and texture interpretation of the rocks below ground**. Examples from Mars Exploration Rovers, showing subsurface materials important to understanding the geology. <u>Left:</u> Basal layer of stratified, sulfate-bearing sedimentary deposits (orange), which overlie the ejecta of Endurance crater and older sedimentary layers. <u>Right:</u> Silica-rich deposits at the Spirit landing site, covered by centimeters of regolith. The interpretation of these materials as hydrothermal completely transformed the interpretation of the site. MER Opportunity/Spirit Pancam images c/o NASA/JPL-Caltech*

The two highest-priority measurements for subsurface characterization would be subsurface structure and composition. Ground-penetrating radar and electromagnetic sounding are examples of the techniques that could provide information to better understand local stratigraphy. They could be used to augment surface observations with a continuous cross-section of the subsurface to meters depth, thereby providing context for evaluating stratigraphy and setting. Key measurements would be lateral and depth variation in density, composition, or electrical conductivity, and depth to discontinuities. Gamma ray techniques could provide the ability to sense to >5 cm depth scientifically important materials that would otherwise not be investigated. Detection at shallow depth of elements associated with key minerals– sulfates (S), silica (Si), carbonates (C), or highly hydrated minerals (H) – could pinpoint locations for further exploration.

3.3 Objective B: Assess the Biosignature Potential Preservation Within the Selected Geological Environment and Search for Potential Biosignatures

3.3.1 Scientific Foundation

3.3.1.1 Introduction

In this section we discuss how the search for biosignatures is conducted on Earth. Essential components of the search are establishment of the original environment conditions under which the deposits being examined accumulated and the potential for preservation of the biosignatures both at the time of deposition and during subsequent history. The implications for Mars are then examined. The section concludes with a discussion of the importance of detection of organic carbon and what other measurements need to be made to assess the evidence for past habitability and preservation in the rock record.

<u>The Mars 2020 rover would…</u>

*…be able to begin a search for the signs of past life on Mars both using its own instruments **and** by enabling the possible future return of the most promising samples to Earth.*

3.3.1.1.1 Definition of Potential Biosignature and Definitive Biosignature

A biosignature (a "definitive biosignature" or DBS) is an object, substance and/or pattern whose origin specifically requires a biological agent. Examples of DBS are complex organic molecules and/or structures whose formation and abundances relative to other compounds are virtually unachievable in the absence of life. A potential biosignature (PBS) is an object, substance and/or pattern that might have a biological origin and thus compels investigators to gather more data before reaching a conclusion as to the presence or absence of life. The usefulness of a PBS is therefore determined not only by the probability that life created it but also by the improbability that nonbiological processes produced it. Accordingly, because habitable planetary environments could create nonbiological features that mimic biosignatures, these environments must be characterized to the extent necessary to provide a context for scientific interpretations.

3.3.1.1.2 How A Biosignature Can Become a Definitive Indicator of Life

Our concepts of biosignatures and life are inextricably linked. To be useful for exploration, biosignatures must be defined in ways that not only link them to fundamental attributes of life, but that also allow them to be measured and quantified. Universal attributes of life on Earth include its complex interacting physical and chemical structures, its utilization of free energy and the production of biomass (both organic structures and inorganic mineral phases) and wastes, and phenomena that can be sustained through self-replication and evolution. However, we cannot expect all of the universal attributes of life to be expressed in ancient planetary materials. Useful biosignatures must be preserved and be amenable to detection. These can be broadly organized into three categories: physical, biomolecular, and metabolic. Examples of physical features include individual cells and communities of cells (colonies, biofilms, mats) and their fossilized counterparts (mineral-replaced and/or organically preserved remains). Another example is biominerals, which are inorganic mineral structures that serve a functional use (e.g. magnetosomes in magnetotactic bacteria). Molecular biosignatures are those structural, functional, and information-carrying molecules that characterize life forms (e.g. on Earth these are lipids, proteins and nucleic acids). Metabolic biosignatures are characteristic imprints upon the environment of the processes by which life extracts energy and material resources to sustain itself – e.g., rapid catalysis of otherwise sluggish reactions, isotopic discrimination, mineral formation influenced by biological activity, and enrichment or depletion of specific elements. Significantly, examples can be found of abiotic features or processes that bear similarity to biological features in each of these categories. However biologically mediated processes are distinguished by speed, selectivity, and a capability to invest energy into the catalysis of unfavorable processes or the handling of information. These processes can create features that can in turn be recognized as having biological origins.

3.3.1.1.3 Searching for Biosignatures on Mars: Challenges and Caveats

A Mars exploration strategy should accommodate an array of habitable conditions and biota that probably differ to an unknown extent from those on Earth. On one hand, 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. On the other hand, differences from terrestrial life become increasingly possible, and ultimately probable, with increasing levels of biochemical specificity (e.g., nucleic acids and peptides). Highly diagnostic biosignatures recognized in studies of terrestrial systems (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 processes. 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. Even though life detection strategies for Mars should ideally allow for the detection and characterization of Earth-like biosignatures, the highest priority should be given to approaches and methods that define and seek biosignatures in a broader sense.

3.3.1.2 Understanding Biosignatures and their Environmental Context on Earth

3.3.1.2.1 Categories Of Biosignatures And How Each Category Can Be Definitive

The diverse types of biosignatures can be grouped into six categories according to observations that are ever expanding as a result of new analytical techniques for characterizing them (Table 3-2). Within each category, the potential for the observed features to be biological varies significantly over a broad range of observations. For example, all organic matter observations are potentially biological in nature and thus are regarded as potential biosignatures (PBS), but different types of observations are capable of distinguishing biotic from abiotic organic matter with varying degrees of confidence (see Section 3.3.1.4.2). The presence of organic carbon alone cannot make this distinction, whereas molecular compositions can with the highest level of confidence (Summons et al. 2011). Examples for each category of biosignatures can be found in Table 3-2.

Table 3-2. Potential biosignatures are more than just organics*. Categories and examples of potential biosignatures.*

PBS category	Description	Examples
Organic signatures	Organic matter features, including organic carbon, character, and particular molecular structures, abundances, and/or molecular weight distributions	Organic C presence, character (elemental composition, bond and functional group abundances, aliphatic/aromatic content, isotopic compositions, spatial distribution at microscales), and molecular compositions.
Stable isotopic patterns	Stable isotopic patterns in organics or minerals not consistent with abiotic processes	C, N, S, Fe isotopic distributions consistent with biological fractionation and ecological influence on a larger scale (local environment to planetary) isotopic system.
Minerals	Minerals that compositionally or morphologically have been associated with biological activity on Earth	Magnetite grains from magnetotactic bacteria (e.g. true biominerals) or organomineral complexes (e.g. framboidal pyrite)
Chemicals	Evidence of chemical equilibria or disequilibria that are inconsistent with abiotic processes	Spatial variations in inorganic elemental abundances and/or ratios of redox and pH sensitive molecular species that are consistent with localized metabolic activity and/or localization of biomass (e.g. reduction spheroids or concretions).
Microscale Fabrics & Structures	Microscale rock or mineral fabrics and structures consistent with the formation by or fossilization of biological entities	Cellular structures, encasement, and pseudomorphs (i.e. microfossils), endolithic borings
Macroscale Fabrics & Structures	Macroscale rock fabrics and structures that are not consistent with formation by biological processes	Microbial mats, stromatolites, reefs, bioherms

Finding B-1: Categories of potential biosignatures (PBS) on Mars consist of chemical, isotopic, mineralogical and morphological features that can be created by life and also appear to be inconsistent with nonbiological processes.

3.3.1.2.2 Biosignature Record Reflects All Aspects Of The Environmental Contexts And "Life History" Of Biosignatures

Our confidence in identifying a biosignature in a rock not only depends upon whether that signature could be identified by its inherent properties (e.g. chemical composition, mineralogy, structure or isotopic composition); it also depends upon understanding the geologic context in which the potential biosignature occurs. For example, it would be important to know whether the rock unit hosting the biosignature was likely to have formed in a habitable environment capable of supporting such biological entities and whether the subsequent processes affecting the rocks would have enabled the biosignature to be preserved to the present day. Perhaps the most important aspect of geologic context would be whether processes occurred that could have produced the observed biosignature-like feature abiotically.

Multiple complementary measurements are required in order to assess the processes that have created features that were preserved in a geologic deposit. The studies of PBS in early Archaean rocks on Earth illustrate the importance of careful, multi-scale integration of observations of the primary formation environment, the post-formation geological history of rocks formed in that environment, and the interpreted origin of the PBS. Studies of the 3.83 Ga banded iron formation of Greenland illustrate this point. The negative $\delta^{13}C$ of graphite inclusions within apatite of 3.83 Ga banded iron formation metamorphosed to amphibolite facies was presented as evidence of life on Earth at that time (Mojzsis et al., 1996). This claim was later disputed as the rock type was reinterpreted as a highly deformed and metamorphosed igneous rock (Fedo and Whitehouse, 2002). This example indicates the Mars 2020 rover should perform multiple *in situ* measurements in order to establish the geologic context critical to the confident identification of PBS, whether those PBS are detected *in situ* or upon analysis of returned samples.

Finding B-2: Understanding the paleoenvironmental context of a geological deposit is essential for determining the origins of any potential biosignatures (PBS) that it might contain.

3.3.1.2.3 Alteration of Biosignatures

Once an organism or community of organisms dies, its imprint on the environment begins to fade. Understanding the processes of alteration and preservation related to a given environment, and for specific types of biosignatures, is therefore essential. This would be true not only in the search for fossil traces of life on Mars, but also for extant life. For example, metabolic end products that are detected at a distance, in time and space, from their source, may be subject to some degree of alteration. 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 favorable for another. These factors include diagenetic processing from water, heat, and pressure, radiation and oxidation degradation, and physical destruction by impact shock, wind and water agitation and fragmentation, abrasion, and dissolution. These factors might have varied substantially from one geologic deposit to the next, even among sites that had been habitable in the past. Accordingly the effectiveness of any assays to confirm the presence of DBS depends fundamentally on whether any biological materials and structures have been preserved with a fidelity that would be sufficient to permit their detection (Summons et al., 2008).

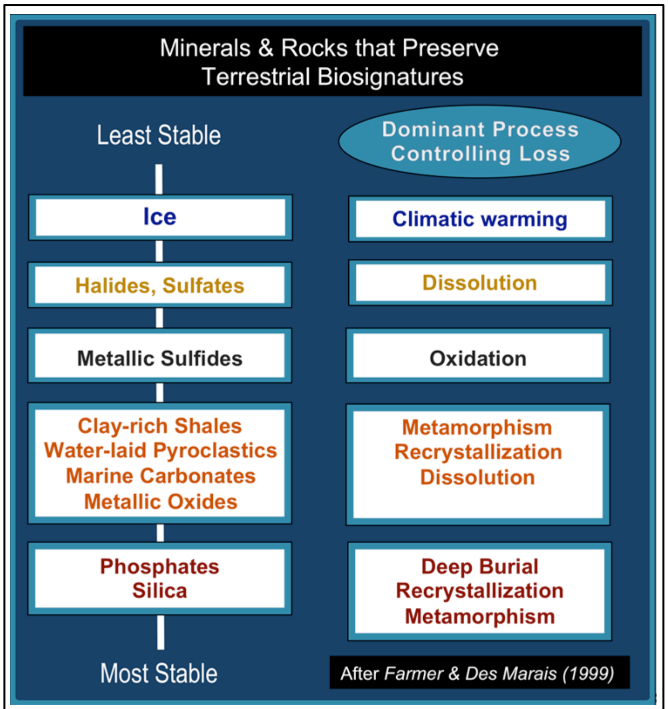


Figure 3-10 Not all rocks are preserved for the same duration. *Many types of biosignatures recognized in terrestrial materials can be preserved in(or as) a wide range of solid materials, which have a wide range of stability against terrestrial weathering and transformation processes. Biosignatures preserved in ice are preserved only as long as climate preserves the ice. Biosignatures preserved in phosphate minerals or silica can be quite resistant and succumb only to extensive recrystallization during metamorphism. After Farmer and Des Marais (1999).*

The long-term preservation of PBS and various evidence of paleoenvironments would be substantially enhanced by their entombment within mineral precipitates like silica, phosphates, carbonates and metallic oxides and sulfides as well as fine-grained sediments such as shales and siltstones (Fig. 3-10; Farmer and Des Marais, 1999). In addition, authigenic[2] cements can permineralize[3] and/or replace inorganic sedimentary frameworks and microbial fossils during early diagenesis.

However, these host sediments are themselves vulnerable to destruction by environmental processes acting over geologic time. The persistence of various sedimentary materials is determined substantially by

[2] authigenic cement – a cement that was generated where it is found or observed
[3] permineralize – the process whereby a framework is filled and made solid by the precipitation of minerals

their physical and chemical properties. Differences in such properties create differences in survival (residence times in Earth's crust) that span several orders of magnitude. As Figure 3-10 indicates, phosphates, silica, carbonates and shales are effective repositories of paleobiological and paleoenvironmental records.

Finding B-3: The existence of biosignatures in ancient rocks is conditional on the presence of a past habitable environment, the past presence of biota that could produce potential biosignatures, and subsequent conditions that have been consistent with preservation of those biosignatures.

Each category of biosignature differs from the other categories with respect to the set of processes that are required for its preservation or that could degrade or destroy the biosignatures (Table 3-3). Organic compounds are susceptible to chemical reactions that progressively introduce oxygen to their reduced carbon structures, the ultimate product of which is carbon dioxide and water. Biological (microbial) or non-biological processes may induce oxidative degradation. Other mechanisms of degradation include radiolysis and photolysis--both can be oxidative in nature. Thermal processing can also degrade organic biosignatures where heat transforms biomolecules through the progressive loss of functional groups and rearrangement of carbon skeletons to more stable structures (Engel and Macko, 1993). Stable isotope ratios are susceptible to diagenetic processes, for example the degradation of organic matter to CO_2 that could crystallize as secondary carbonate corrupts primary carbon isotope signatures. Mineral biosignatures can be altered by dissolution, oxidation, reduction, metamorphism, or recrystallization. Microscale rock fabrics and structures are particularly susceptible to dissolution and recrystallization.

Table 3-3. Even after formation, it is easy to destroy PBS. *Major factors that destroy or degrade PBS*

PBS Category	Examples
Organic signatures	Microbial degradation, oxidation, radiolysis or photolysis, thermal degradation
Stable isotopic patterns	Dissolution/recrystallization, thermal alteration
Minerals	Dissolution; oxidation or reduction; transformation to other phases due to temperature, pressure, and/or migrating fluids
Chemical biosignatures	Dissolution; oxidation or reduction; transformation due to temperature, pressure, and/or migrating fluids
Microscale Fabrics & Structures	Dissolution; recrystallization due to elevated temperatures and/or pressures, or water-rock interactions
Macroscale Fabrics & Structures	Deformation and fracturing due to elevated temperatures and/or pressures

Finding B-4: Each category of biosignatures differs from the other categories with respect to the particular set processes that are most important for altering or destroying the biosignatures.

The effectiveness of a given environment and the geological deposits it produces to preserve biosignatures is referred to as the biosignature preservation potential (BPP) of that environment or geologic deposit.

Finding B-5: Assessing the potential for preservation of any given type of biosignature requires interpretation of past geological environments and processes. This interpretation requires measurements of rock chemistry, mineralogy, oxidation state, rock texture, morphology and context.

3.3.1.2.4 Biosignature Interpretation Is Enhanced By Investigating Multiple Paleoenvironments Along With Any Associated PBS

The interpretation of a PBS as well as the BPP of its host deposit is strengthened further if an investigation also characterizes associated deposits that have preserved evidence for their environments of formation and their geologic history across broader spatial and temporal scales (see Fig. 3-11). This could only be accomplished by navigating to multiple outcrops containing a variety of rock types of varying relative ages, surveying the contacts between these units to establish a chronological framework and performing detailed investigations of multiple outcrops representing these different environments to determine whether any PBS are present and to assess the BPP of the unit. For example, the detection of microbial PBS associated with an apparent fluvial unit would be enabled by a horizontal traverse from its onshore facies, which might contain remnants of phototrophic biofilms[4] or cryptoendoliths[5] (Friedmann, 1982; Omelon et al., 2006; Wierzchos et al., 2001) to offshore depositional facies which may contain detrital remnants of planktonic organisms (Murray et al., 2012) or ice algae (Horner et al., 1992). Traversing vertically through a time transgressive succession of deposits at one landing site representing different depositional environments, e.g. lacustrine, evaporitic, aeolian and volcanic ash flow sediments, would determine whether certain PBSs are associated with specific environments and whether these environments were both habitable and favored preservation. Finally, surveying geological units that have experienced a range of post-depositional environments including heating, high temperature fluid alteration and deformation resulting from the intrusion of igneous units or meteoritic impact provide field evidence as to whether any interesting features are potentially biogenic or abiogenic in origin.

Finding B-6: A field traverse to conduct lateral and stratigraphic surveys of multiple geologic deposits would be required to assess biosignature preservation potential (BPP) and any potential biosignatures (PBS) in a geologic deposit with a record of multiple paleoenvironments.

3.3.1.3 Potential Martian Biosignatures In Their Environmental Context

3.3.1.3.1 Look For PBS In The Most Promising Places: Habitable Paleoenvironments Having High Preservation Potential

Mars has retained diverse geologic deposits that vary widely in the type, abundance, and quality of evidence of ancient habitable environments and, perhaps, evidence of PBS. The strategy to characterize habitability and BPP during rover traverses in order to optimize the search for PBS is a key aspect of the overall search for evidence of past martian life. Key considerations are:

Habitability: In the context of Mars exploration, "habitability" has been previously defined as the potential of an environment (past or present) to support life of any kind, and has been assessed largely in reference to the presence or absence of liquid water. To support site selection, additional metrics should be developed for resolving habitability as a continuum (i.e., more habitable, less habitable, uninhabitable) rather than a yes-or-no function, and this would require that additional determinants of habitability to be characterized (See Section 3.2). Accordingly the selection of landing sites should assess the capacity for any candidate sites to have sustained past life.

Preservation Potential: Tests for the presence of PBS depend fundamentally upon sufficient geological preservation of materials and structures (e.g., Summons et al., 2011), as well as maintenance of sample integrity starting the moment the rover encounters the sample to the time when tests are conducted in Earth based laboratories, which could be many years later.

[4] biofilms – any population of microorganisms whose cells adhere to each other to form a film on a surface
[5] cryptoendoliths – organisms that live inside solid materials such as rocks or other solid substrates

Potential Biosignatures: The tests for assessing the presence of any PBS would be different for each of the six categories of biosignatures identified above (Table 3-2). It is difficult to predict which *in situ* observations would provide the most useful information for this assessment. Single observations may suffice, such as detecting particular organic molecular characteristic, structures, and chemical distributions (Summons et al., 2007) or morphological observations (e.g. microfossils) (Summons et al., 2011). However a suite of coordinated observational tests that could detect multiple categories of PBS would greatly improve the confidence in identifying any PBS and understanding their preservation (e.g. Allwood et al. 2008; Eigenbrode, 2007).

Characterization of the environmental features and processes on Mars that preserve specific lines of biosignature evidence is a critical prerequisite in the search for life. Accordingly, an assessment of the capacity for any sites to have preserved such evidence should be a part of the process to select landing sites and target localities along the rover's traverse (Fig. 3-11).

Major Finding B-7: To search for potential biosignatures, it is necessary to (a) identify sites that very likely hosted past habitable environments, (b) identify high biosignature preservation potential materials to be analyzed for potential biosignatures, and (c) perform measurements to identify potential biosignatures or materials that might contain them.

However during rover operations, the strategy to first evaluate habitability and BPP in an area, and then to search for PBS, though logical, would typically not be practical. Because a rover rarely returns to previously visited locations, it must complete all observations and sampling before it moves to the next location. Accordingly, evaluations of habitability and BPP and any measurements of PBS must be executed concurrently before leaving a particular location.

Finding B-8: Although it would be logical to assess habitability and biosignature preservation potential before seeking potential biosignatures, for practical considerations, evidence for all three would be sought concurrently during exploration at a particular rover location.

3.3.1.3.2 The Capability To Search For Multiple PBS Categories Is Critical To Optimize Search Strategy In The Face Of The Unknown And Unexpected

Accurately predicting which categories of PBS are most likely to exist at a site would be difficult, if not impossible. Even with high levels of confidence in paleoenvironmental interpretation from orbital data, in most cases it would not be possible to exclude any given category of PBS from the list of candidates that could be preserved at that site. Therefore to maximize the chance of detecting any PBS that may exist at a site, it is essential to be prepared to detect PBS of all six categories. This would require:

1. Direct detection of PBS: Some categories of PBS may be directly identified with the kinds of instruments that the Mars 2020 rover could reasonably be expected to implement. For example the rover would likely to include a camera for detecting macroscopic morphological PBS and an organic detection capability for detecting organic PBS. However the rover would be unlikely to include thin section preparation capabilities for detecting microfossils.

2. Measurements for seeking, identifying and characterizing promising materials that may contain PBS recognizable only with sophisticated Earth-based preparation/analysis methods: Some categories of potential biosignatures, such as potential microfossils and isotopic signatures, would be extremely difficult to detect *in situ*. Measurements of isotopic PBS are limited to terrestrial laboratory analyses because the isotopic systematics of Mars are not characterized sufficiently to enable the detection of isotopic PBS. On Earth, isotopic patterns

can be very robust biosignatures of communities and specific metabolisms in ways that are very informative about paleoecosystems and subsequent alteration of the geological record. However, interpretation of observed isotopic patterns is entirely dependent on understanding the sources of carbon, the relative abundances of the major crustal carbon reservoirs, and the isotopic fractionation factors for metabolisms at the time the isotopic record was formed. Bulk, spatially resolved, and molecularly resolved isotopic measurements of returned samples would substantially help build the knowledge base needed to recognize martian isotopic PBS. However, it would be important for the *in situ* mission to identify materials that have a high potential to contain these biosignature types, as such materials would be desirable to select as samples for Earth return. The 2020 *in situ* strategy would be to identify habitable environments and materials therein that have high potential for preservation of biosignatures.

This dual approach would be essential not only because we cannot predict which types of PBS might be present, but also because if multiple types are present the confidence in interpretation increases dramatically with combined observations of different categories of potential biosignatures (Table 3-2). Also the ability to search for materials that might contain biosignatures not recognizable in the field would be critical because, as terrestrial paleobiology studies show, there are numerous instances where PBS are only detectable using complex sample preparation and analytical techniques that cannot conceivably be implemented on the Mars 2020 rover. Key examples include microfossils, which require thin section preparation or acid digestion and hand picking. Another example are patterns of stable isotope abundances that are observed in thin section preparations, followed by detailed SEM and *in situ* microprobe work (e.g. Bontognali et al., 2012; Lepot et al., 2013) and that might be interpreted as PBS.

Finding B-9: Full evaluation of the potential for biology must include the ability to detect multiple categories of PBS *in situ* and characterize their geologic context (including habitability and biosignature preservation potential). A thorough characterization and definitive discovery of martian biosignatures would require analysis of samples returned to Earth.

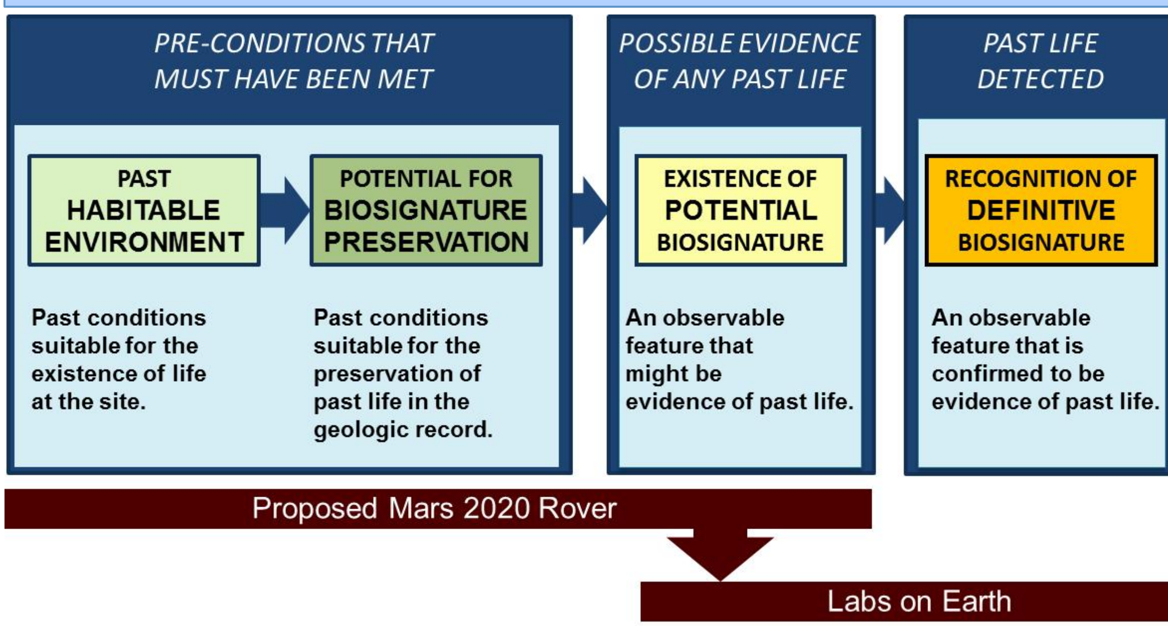


Figure 3-11. Scientific Process for Detecting Past Martian Life. *The rover must assay samples for any evidence of past habitable environments and for the samples' capacity to preserve evidence of past environments and any PBS. Highly promising samples would then be selected for return to Earth-based laboratories that can conduct more rigorous assays for PBS and DBS.*

3.3.1.3.3 Measurements Required to Assess Biosignature Preservation Potential and Detect PBS

Searching for, detecting and interpreting potential biosignatures requires a carefully integrated array of measurements and observations. Integration is critical because identification of PBS requires multiple, lines of evidence spanning micro to macro scales (Allwood et al., 2013), The process of *interpreting* PBS (i.e., to determine if it indicates the presence of a DBS) begins with high quality field observations and continues with measurements that can only performed on returned samples. The success of returned sample analyses fundamentally hinges upon the quality of observations in the field.

Exactly which types of measurements are needed in the field is determined, fundamentally, by the fact that the clues to past habitability, BPP and potential ancient biosignatures reside in the geologic record. As with objective A, to interpret that record requires—at a minimum— an understanding of: (1) the appearance of the rocks (morphology and texture, observed by cameras); (2) their composition (requiring measurements of mineralogy, chemistry, organic matter); and (3) the relationships between morphological features, textures and composition (requiring measurements to be integrated within and between scales). This set of geologic measurements overlaps strongly with the measurements needed to achieve Objective A. The overlap exists because both objectives require, first and foremost, integrated observations of the characteristics of rocks.

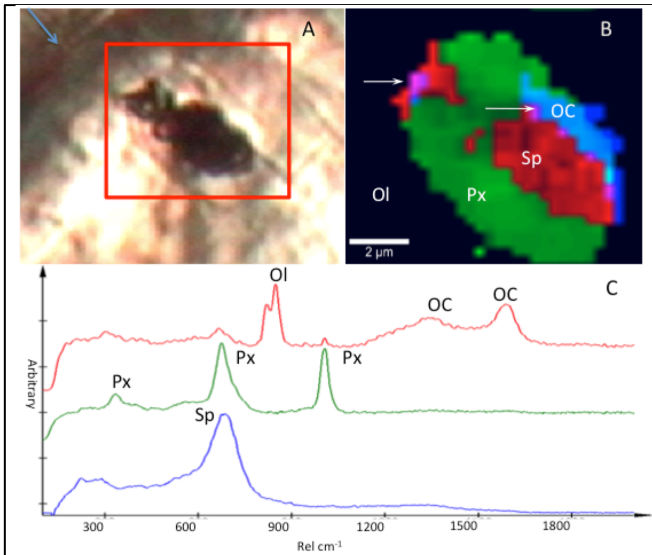


Figure 3-12. Spatial correlation of textural, mineralogical, and chemical data fine scales is crucial for successful detection and interpretation of potential biosignatures – a key new capability for Mars 2020. *Examination of visible light (A) and Raman scattering (B) images of spinel blebs in an olivine phase of the DaG 476 martian meteorite (Steele et al. 2012) reveal a strong spatial association of macromolecular carbon (OC with the spinel, and not with cracks. The carbon is therefore likely not biogenic or a contaminant. C: Representative Raman spectra of Olivine (Ol), Pyroxene (Px), Spinel (Sp) and Organic Carbon (OC). Such spatial correlations are applicable over multiple length scales, from microns to many millimeters, associated with the compositional and textural heterogeneity of numerous synthesis, deposition, and alteration processes.*

As discussed above in the context of Objective A (see especially Section 3.2.2.1.1), a consideration important to astrobiology is the scale at which each measurement is made, and the ability to spatially correlate different measurements within and between scales (as illustrated in Fig. 3-8). Mineralogical, chemical and organic investigations at the scale of individual rock grains (or finer)—and the ability to correlate these data with visible images—are vitally important for interpreting whether rocks were influenced by biological processes. As an example, the detection of carbonate could be significant as a potential target for biosignatures, but its significance would be vastly different if the material occurred as detrital (transported) fragments, in veins deposited at high-temperature after deep burial of the rock or in fine, or *in situ*-formed layers in a sedimentary rock (Morris et al., 2010, McKay et al., 1996). Likewise, the detection of highly polymerized organic material would be significant, but the degree of significance would differ if the material occurred as detrital fragments, veins, inclusions, within carbonates or as fine layers (Steele et al., 2012a, b). The physical distribution of highly polymerized organic material in some instances is necessary but rarely sufficient to suggest a biological origin (Pasteris and Wopenka 2002). Fine-scale observations are also central to interpreting whether rocks may have been affected by processes leading either to preservation or to destruction of biosignatures.

Fine-scale observations of the chemistry and mineralogy may also provide critical insight to the origin of organic matter. For example, organic matter in a basaltic rock could have formed by abiotic reduction of CO_2 at high temperatures (>300°C) and low f_{O2} in the presence of a magnetite / pyrrhotite catalyst (Holm and Hennet 1992, Steele et al., 2013). Alternatively the organic matter could have been formed by biological activity as groundwater migrated through the porous structure of the basalt at temperatures <120°C. Spatially coordinated *in situ* mapping of the mineralogy and organic matter could potentially identify mineral phases that could constrain the temperature of the environment containing the organic matter. Knowing if that temperature greatly exceeds the limits of life on Earth would affect its designation as a PBS. An example of this is polymeric carbon containing inclusions formed during crystallization of martian basalts (Steele et al., 2012).

Twelve martian meteorites have been shown to contain an inventory of a reduced polymeric carbon phase that has a carbon isotope signature that could be mistaken for life. Identification of such a phase allows the understanding of an abiotic "baseline" that would become perturbed by the influence of a possible putative martian organism (Figure 3-12). Such organomineral complexes, which are fine-scale associations of organic compounds and low temperature mineral suites, are potential biosignatures (PBS) that require detailed characterization of composition and context to determine whether they are biotic or abiotic (Perry et al., 2007, Steele et al., 2012). Terrestrial examples of bio-organomineral complexes include the Fe-oxyhydroxides that are produced by the stalk forming Fe oxidizing bacteria *Gallionella ferruginea*, the laminated carbonates of stromatolites, and the organic-rich cores of reduction spheroids (Spinks et al., 2010, Hallbeck and Karsten 1990). If comparable features exist in outcrop on Mars then instruments capable of determining the elemental abundance, the valence state of Fe, the abundance and class of organic compounds and minerals combined with a capability to spatially correlate these observations across two dimensions would be required. The final report of the MRR-SAG came to this same conclusion, namely that an instrument payload that could achieve microscale, ~0.1 mm, mapping of mineralogy, organic compounds, and elemental composition was essential for identifying potential biotic and prebiotic signatures (MRR-SAG, 2010).

Finally, we can also think about what measurements are most important specifically for detecting each category of biosignature (Figure 3-13). For example, macrostructures and textures, such as stromatolites, bioherms, or reefs require context imaging by cameras mounted on the rover. Microstructures and textures require observation by an imager that has a relatively short focal length and could be arm mounted for selective positioning against the rock of interest. Access to micro-scale PBS requires first removing the dust and weathered surface using an abrasion tool. Compositional measurements (mineralogy, chemistry and organics) are needed to detect mineral, chemical and organic PBS, and to observe compositional properties of morphological and textural PBS (Cady et al, 2003).

Finding B-10: The ability to spatially correlate observations of multiple categories of PBS within the context in which they are preserved enhances the ability to detect and interpret biosignature preservation potential and potential biosignatures.

3.3.1.4 Organic Matter and Biosignatures

3.3.1.4.1 Organic Detection *In Situ* Is A Critical Part Of The Search For Martian PBS

Acquiring rock samples having organic matter is a very high priority for MSR scientific objectives (objectives 1, 3-6 and 8 of the E2E-iSAG (2012) report). Organic molecules are precursor materials for life. The production, organization, and processing of organic molecules is central to all biochemistry and cellular structures regardless of the initial carbon source used by microorganisms. The chemistry and distribution of organic compounds in the rock record could provide key constraints on the habitability potential of an ancient environment. Further, the nature of organic matter could help to characterize ancient environments and processes in much the same way that inorganic chemicals and minerals record formation, depositional, diagenesis, and later alteration. Integrating *in situ* organic carbon measurements into the strategic approach for addressing Mars2020 objectives related to biosignatures has the potential for greatly enhancing the science return of both the mission's *in situ* investigations and MSR. There has been a significant flux of meteoritic carbon to the martian surface (Flynn, 1996) over Mars history, and martian meteorite observations indicate that indigenous abiotic organic carbon is associated with igneous and hydrothermal processes (Grady et al., 2004, Steele et al., 2007, 2012a, b, Agee et al., 2013). These observations support the existence of an organic carbon pool on Mars. However the strategy to access any organic carbon reservoirs so that we can advance related investigations would involve extensive field and *in situ* geochemical studies that include at least the capability to measure organic matter. Assuming that the Mars 2020 rover can find rocks having organic carbon, the capability to characterize organic molecular compositions *in situ* would be an optimal approach for assessing BPP and detecting any organic PBS. But if molecular measurements cannot be performed due to limitations in mission resources, an alternative credible approach would be to detect any organic carbon *in situ* and then conduct molecular analyses on samples that are returned to terrestrial laboratories (Fig. 3-11).

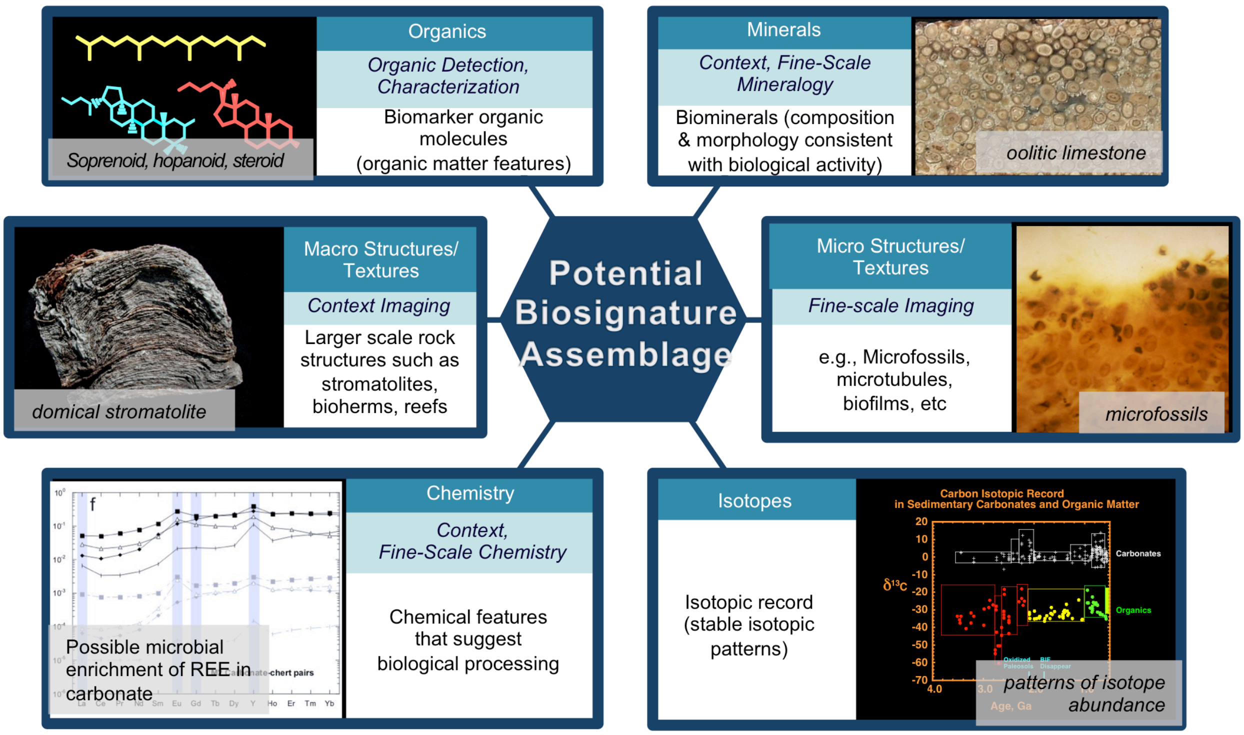


Figure 3-13. Mars 2020 would be able to detect 5 of the 6 types of biosignatures *Links showing Potential Biosignature (PBS) assemblage at an investigation site and the associated analyses. The assemblage of PBS (center) includes six individual varieties, shown in blue boxes. Each of those PBS types could be investigated through specific observations on Mars, shown in italics. Isotopic PBS cannot be studied with the proposed Mars 2020 payload, and would be investigated (after sample return) in laboratories on Earth.*

On Earth, ancient potential biosignatures tend to be accompanied by a degree of ambiguity. For Mars, understanding BPP for each biosignature category and detecting PBS (*in situ* or upon return to Earth) are the first steps. Testing a PBS for evidence that it is a DBS would be the next step and a key motivator for achieving MSR. When combined with observations of non-organic PBS, organic matter detection and characterization greatly enhance the prospects of confirming the presence of any DBS. Thus our confidence in the interpretation of PBS would be greatly enhanced if the presence, character, and molecular nature of any associated organic matter be documented.

Major Finding B-11: The rover must have the capability to detect organic matter and organic potential biosignatures as a threshold requirement in order to credibly address the mission objective to search for evidence of past life.

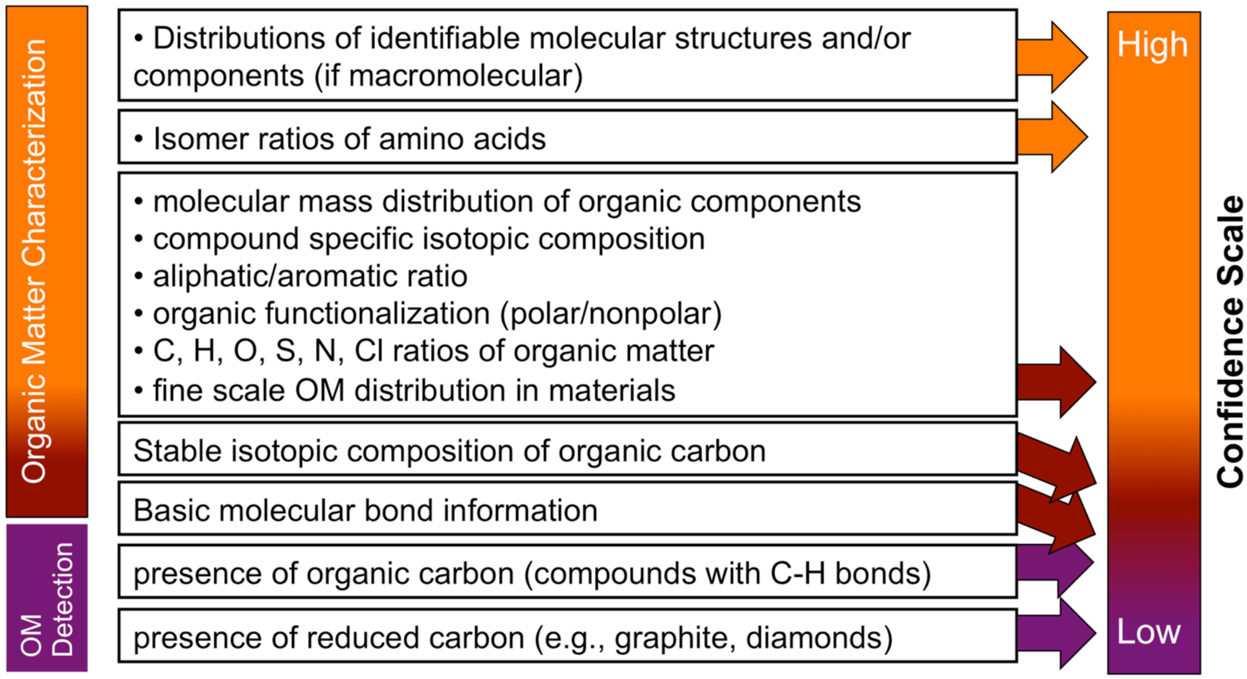


Figure 3-14. Organic molecule detection methods are not as definitive as some types of organic matter characterization. *Confidence of detecting or not Definitive Biosignatures (DBS) for various observation types about organic matter (OM). Observation types in central column, arranged in order of confidence that the observation could yield a definitive biosignature (right column). Left column denotes general type of the observation: detection vs. characterization of the organic matter. Note that the level of confidence provided by a given measurement varies depending on the specific details (e.g. degree of thermal degradation) of the sample being investigated.*

3.3.1.4.2 Confidence In Interpretation Of Organic Potential Biosignatures

Strategies for detecting ancient PBS can involve a range of optical or analytical measurements. Yet not all measurement types have the same diagnostic potential (Fig. 3-14). Some measurements, such as detecting organic carbon, are suggestive but not definitive. Other measurement types provide greater confidence as to whether the feature under investigation has been produced by biological activity. Features that provide intermediate levels of confidence include elemental ratios and molecular mass distributions of organic compounds. When multiple types of measurements are combined, the ability to establish the presence of any PBS improves. For some features the probability of a non-biological origin is so remote that they represent single point diagnostic characteristics. Complex biological molecular structures, e.g., oligomers or polymers, represent such highest confidence biosignatures.

3.3.1.4.3 Methods For Detecting And Characterizing Organic Matter

The vast majority of spaceflight-compatible methods for detecting organic matter that might include potential organic biosignatures can be categorized as types of mass spectrometry, chromatography, spectrophotometry, and binding assays or metabolic assays. Specific instruments that implement one or more of these methods typically levy specific requirements on sample preparation, ranging from "none needed" to (more typically) rather elaborate procedures. Some spectroscopic techniques require little or no sample preparation. Other techniques require some form of sample manipulation (e.g., sample coring/drilling and possibly powdering) that may be followed in numerous methods by some form of extraction of target molecules, either by liquid based methods, heat (pyrolysis), ion bombardment or laser desorption. As a general rule of thumb, increasing the characterization capability of a measurement technique increases the complexity of sample preparation (See Fig. 3-15). Indeed there appears to be a technology gap for spaceflight-ready instruments that could provide moderate to extensive characterization information at high sensitivity yet require little sample preparation.

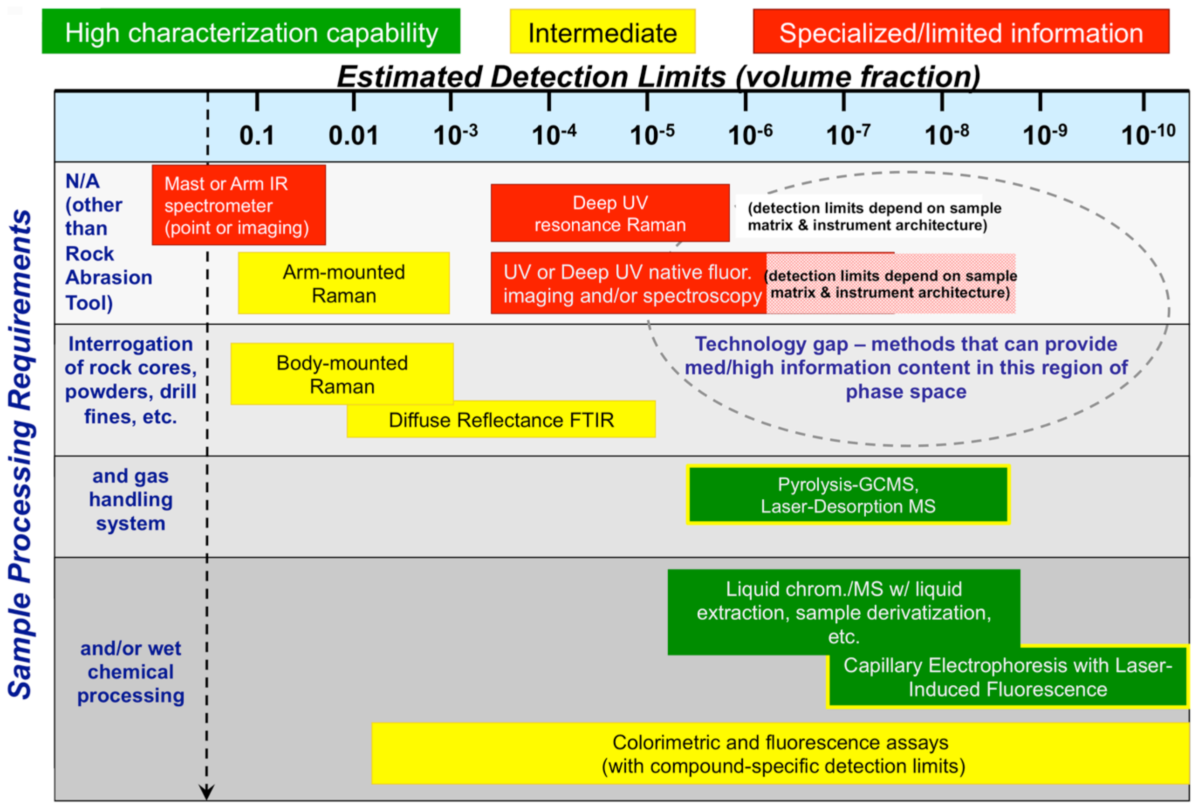


Figure 3-15. Instrument options for measuring organics. *High characterization capacity and low detection limits, in green, are the goals; instrumental methods in yellow and red are less desirable. At this time, no methods with low sample processing requirements have low detection limits and high characterization capability – the technology gap in the upper right part of the figure. Originally prepared for MRR-SAG (2009) and updated by Feldman, written communication, 2013.*

Highly detailed analyses of organic material require multiple complementary methods, realized as instrument suites that give a range of measurement data on common samples. In the case of organic materials in martian samples, an accurate understanding of the nature of any organic material requires the following information: spatial distribution, context with surrounding minerals, presence and ratio of carbon to nitrogen, hydrogen or oxygen bonding, aliphatic to aromatic carbon ratio, molecular weight distribution, chirality, and isotopic composition of C, N, O and H. All of this information could be gained in terrestrial laboratories using a mixture of *in situ* (in the strict sense) and bulk analysis tools. The inference as to the whether the distribution of organic material is abiotic or biotic would place the most stringent and broad-based demands on multiple crosschecking instruments operating on a range of sample types (thin sections, fresh fracture surfaces, bulk powder, mineral separates, etc.) (e.g., McKay et al., 1996; Steele et al., 2012). The extremely sensitive and fine-scale capabilities of these ultimate analyses, the protocols and appropriate blanks of which may not even be known until broad initial sampling would be completed, would be essentially impossible for a single rover mission to achieve on Mars. Therefore the question becomes what analyses could be conducted to ensure the search for potential organic biosignatures and the caching of suitable samples for return to Earth that would ultimately enable the most robust and complete set of analyses possible.

The threshold requirement for *in situ* organic analysis, as detailed for Finding B-12, would be able to detect organic matter via the identification of reduced carbon compounds in near-surface materials. Baseline concepts improve on this requirement by providing increased levels of organic PBS characterization in support of science and sample return selection objectives. There is a range of flight-worthy instrument types, with various sample processing requirements, that readily provide the threshold and baseline capabilities. One way to organize and depict such capabilities is with limit of detection (LOD) for organics as measured in weight or volume fraction (Fig. 3-15), Mast or arm-mounted instruments such as IR, UV, or Raman spectrometers require no sample acquisition and minimal processing and can detect organics with LODs ranging from percent levels down to parts-per-million (ppm) or even lower in select cases. Uniformly lower LODs, ranging from ppm to parts-per-billion (ppb) and below, are within the capabilities of techniques such as mass spectrometry, liquid chromatography, and electrophoresis. Generally these techniques require sample acquisition and processing that typically involves the generation of fine powders that are delivered to a controlled-pressure analysis vessel. A notable exception is the ambient laser desorption method, such as used on ExoMars, that does not require such ingestion. These rather involved methods also provide a more comprehensive organic characterization compared to mast and arm-mounted instruments, which may have somewhat limited characterization capabilities. On the other hand, a caching rover mission with limited resources would need to identify samples to return as efficiently as possible. As long as organic LODs are low enough, this efficiency requirement suggests that instruments such ambient spectrometers and spectrophotometers are sufficient to meet the overall mission objectives for PBS detection.

Finding B-12: A sample-caching mission must survey many targets for organics and document their environmental context; some surface-based spectroscopic techniques are the most practical way to meet this requirement. Although molecular analysis techniques that use processed samples can characterize organic PBS more comprehensively than surface-based spectroscopic techniques, a sample-caching mission with constrained resources must place higher priority on the more fundamental effort to detect organics and understand their spatial distribution.

3.3.1.4.4 *In Situ* Spectroscopic Measurements of Organic Matter – Threshold

Several advantages of spectroscopic measurements of organic matter include minimal sample preparation, rapid acquisition and data product analysis, high frequency of analyses and measurement of both inorganic and organic components with high spatial resolution. Spectroscopic instruments can achieve a large number of non-destructive, contact measurements on samples prior to drilling and caching. Furthermore, multiple spot, line scans or point mapping of a sample surface could provide a rapid and comprehensive analysis of a sample. Spectroscopic techniques are therefore advantageous for detecting reduced carbon or organic carbon and they are ideal examples of threshold measurements for this mission.

For the threshold mission, the instrument must detect the presence of reduced carbon, which could be in any form such as graphite or macromolecular material as well as aromatic or aliphatic species. Due to the nature of spectroscopic techniques several categories of measurements can distinguish reduced or organic carbon signals from mineral spectral features such as carbonates or silicates. The requirement would allow the simultaneous detection of the spatial distribution and therefore the context of organic matter within the surrounding minerals. This provides more information about the provenance of the organic material, i.e., within igneous minerals, clays, etc.

The required detection sensitivity is $<10^{-5}$ to 10^{-6} w/w reduced / organic carbon species averaged over the entire analysis area, and/or detect $<10^{-2}$ to 10^{-4} w/w, if organics can be spatially resolved at <100 µm per analysis area.

There are several possible challenges to the use of spectroscopic techniques for *in situ* measurements of samples on Mars. Although spectroscopic techniques can analyze unprepared surfaces, previous experience has shown that some abrasion or cleaning of the surface would be necessary to reveal non-weathered surfaces (i.e., the RAT tool on MER). Any spectrometer should be able to tolerate surface roughness achieved by a preparation tool such as a rock abrasion tool (RAT). Measurements should also be robust against non-specific interferences from luminescence, grain size effects, sunlight or fluorescence that interfere with the measurement fidelity.

3.3.1.4.5 Augmented *In Situ* Organic Characterization – Baseline

A more detailed *in situ* characterization of any detected organic matter would substantially improve our search for and assessment of potential biosignatures. This improvement comes in the following dimensions: 1. The ability to identify complex organic matter and types of compounds that could be associated with life; 2. The ability to distinguish biological sources from potential sources of abiotic organics; 3. The increased confidence in recognizing other potential biosignatures detected in spatial association with the organics; 4. The *de facto* high biosignature preservation potential of any material hosting significant complex organics of any origin; and 5. The use of all of these factors during the mission to maximize the scientific basis for selection of samples for return. As such, *baseline* and *enhanced baseline* mission concepts that perform more thorough organic characterization as depicted in Figure 3-14 would increase confidence in PBS detection and result in greater overall science return than the threshold concept could provide.

Given mission constraints, improved characterization of organic constituents could reasonably be provided by a second spectroscopic technique that detects properties of organic matter complementary to the properties detected by the threshold spectroscopic technique. For example, a baseline flight instrument that detects organics via deep UV fluorescence would complement a threshold instrument that utilizes infrared spectra. Such an improvement could be realized without requiring additional resources associated with collecting or processing samples (see below and Table 3-4). The combination of two techniques such as these would collectively lower detection limits and improve the characterization of any organic constituents.

Finding B-13: Additional *in situ* organic detection and characterization of organic matter, such as provided by a second spectroscopic technique in a baseline mission, would significantly improve our understanding of biosignature preservation potential and ability to detect potential organic biosignatures.

3.3.1.4.6 Detailed Characterization and Molecular Analysis – Enhanced Baseline

If mission resources are available, more detailed characterization and molecular analysis of organics (Fig. 3-14) would arguably provide the optimal basis for organic PBS detection and selection of samples for caching and return. Given the complex conditions required for habitability and preservation, it is possible that the most compelling potential biosignatures may be found only in some outcrops or exposures examined by the rover. Given the points above, the distribution and structural character of any detected organics are the most sensitive indicators of such PBS. As such, identification of complex, functionalized organics localized to a host rock with high BPP, as distinguished from a potentially broad-based but trace distribution of reduced carbon, would provide a powerful "triage" for priority cache sample selection. Moreover, the ability to characterize aromatic, aliphatic, and other structural moieties (e.g., hetero-substituted oligomers), along with other parameters such as atomic/isotopic composition and fine-scale spatial distributions of complex organics, would provide the information needed to assure the broadest representative distribution of samples to maximize the diagnostic value of materials returned to Earth.

Table 3-4. Organic detection and some amount of organic characterization may be achieved without sample acquisition requirements. *Example organic analysis techniques such as infrared and Raman spectroscopy and mass spectrometry can be organized according to their sampling requirements and options. The four "star" levels qualitatively indicate the relative ability of each technique to perform organic detection, organic characterization, or molecular analysis measurements of potential biosignatures (Fig. 3-13). Techniques that address the full range of organic characterization and molecular analysis generally require sample acquisition (core or powder) and some manipulation. Only returned samples (MSR) enable the complete and ultimate realization of every measurement type.*

		Example Techniques															
	Sampling Options ➔	In Situ, Tailings, or Acquired Sample							Acquired Core or Powder								MSR
	Analysis Type/Envt. ➔	Surface Analysis - Mars Ambient						Surface Analysis - Vacuum			Bulk Analysis - Vacuum and/or Sealed Liquid Proc.						Array of lab techniques
	Target Approach ➔	Mast/Large Standoff		Close Standoff or Working Distance							Ingested/Processed Powder						
Category	**Measurement**	IR	Raman	IR	Raman	UV Fluor.	Amb-LDMS	LDMS	L2MS	SIMS	Pyr/MS (EGA)	Pyr/GC-MS	HPLC-MS	CE/LIF	Fluor. Assay	Pyr/CELAS	
Organic Detection	Reduced C (e.g., graphite) or Organic C	★	★	★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★	★★★		★★★★
Organic Characterization	Bulk isotopes ($\delta^{13}C$)									★	★★	★★★	★★★			★★★	★★★★
	Fine spatial distribution			★★	★★★	★★★	★★★	★★★	★★★	★★★	★★ - if fine-scale sampling						★★★★
	C, H, O, S, N, Cl ratios						★	★	★	★★	★	★★★	★★★				★★★★
	Functionalization (polar/nonpolar)						★★	★★	★★	★★	★★	★★★	★★★	★★	★★		★★★★
	Aliphatic/aromatic ratio			★	★★	★★	★	★	★★		★★/★★★ - depending on implementation						★★★★
	Compound specific isotopes										★	★★★	★★★			★★★	★★★★
	Molecular mass distribution						★★★	★★★	★★★	★	★★	★★★	★★★	★			★★★★
	Isomer ratios of amino acids						★	★	★			★★★	★★★	★★★			★★★★
Molecular Analysis	Distributions of molecular structures and/or components (if macromolecular)						★★	★★	★★		★	★★/★★★	★★★	★★★	★★★		★★★★
	Options						MS/MS	MS/MS			MS/MS, Derivatization, Thermochemolysis, Hydropyrolysis, Combustion						

Key				*Potential* to address within relevant range	
IR	infrared reflectance spectroscopy	**Pyr**	pyrolysis		
UV Fluor.	ultraviolet fluorescence spectroscopy	**EGA**	evolved gas analysis	★	"limited"
Amb	Mars ambient pressure (no vacuum insertion)	**GC-MS**	gas chromatography mass spectrometry	★★	"moderate"
LDMS	laser desorption mass spectrometry	**CELAS**	cavity-enhanced laser absorption spectroscopy (TLS, CRDS)	★★★	"high"
L2MS	two-step laser mass spectrometry	**HPLC-MS**	high-performance liquid chromatography mass spectrometry	★★★★	"complete"
SIMS	secondary ion mass spectrometry	**CE/LIF**	capillary electrophoresis/laser-induced fluorescence		

Example Options for Organic Characterization and Molecular Analysis. Table 3-4 provides information on a selection of potentially flight-compatible techniques to measure organics at increasing confidence levels of characterization and molecular analysis (Fig. 3-14). Techniques that do not require acquisition of a sample, shown in the columns under "Outcrop/*In Situ* (Unaltered, Abraded/Tailings)" are all Mars ambient surface analyses. The threshold concept incorporates some of these techniques, such as Raman and UV fluorescence spectroscopy, which could address Organic Detection and some Organic Characterization measurements. Such techniques, as well as ambient laser desorption sampling methods, could also be applied to acquired samples, such as cores, to provide additional subsurface and organic characterization capabilities. Techniques requiring samples both to be acquired and inserted or ingested into a controlled pressure environment, such as high vacuum, would be able to characterize sample surfaces and to perform bulk analyses. For example, the SAM investigation on MSL provides a suite of Pyr/MS (EGA), Pyr/GC-MS, and Pyr/CELAS analyses of bulk powders loaded into ovens. Generally the full suite of organic characterization and molecular analysis measurements, with their associated qualitative improvement in detection limits, specificity, and informational content, involve collection and some level of processing of solid samples. Such instrumentation would offer a qualitative leap in science capability compared to threshold and baseline specifications. Given expected resources required for techniques toward the right side of Table 3-4, these would be expected to be identified with an enhanced baseline (i.e., beyond the baseline) concept.

Finding B-14: Significantly higher levels of *in situ* organics characterization and molecular analysis capability, above the baseline concept, are possible with more complex techniques that provide diagnostic structural detail of potential organic biosignatures. The sampling requirements of these techniques generally preclude their inclusion in the baseline scope.

3.3.1.4.5 Organic Matter Measurements *In Situ* vs In Earth-Based Labs

To maximize the chances of detecting any PBS or, at least, materials that have a high probability of hosting a PBS, measurement facilities for as many categories of PBS as possible should be within the rover's analytical toolkit. From this perspective, the mission concept prioritizes *breadth* (a wide range of measurements of a wide range of sample targets) over *depth* (a smaller number of deeper measurements of fewer samples overall) in order to achieve its sample-caching goal in parallel with its *in situ* objectives. As such the threshold capabilities of the rover include imaging, mineralogy, fine-scale elemental chemistry, and organic chemistry, over a range of spatial scales.

Given the particular importance of organic compounds as potential signatures of ancient life, providing an *in situ* capability for their identification in selected samples is a fundamental aspect of the biosignature search and of the selection of samples to cache. As documented elsewhere in this section, the presence of organic matter allows both (i) the possibility of an endogenous martian cycle for the synthesis of complex organics within a habitable zone, as well as (ii) the general preservation of all types of biosignatures, a key factor owing to the uncertain taphonomic conditions[6] of that zone over geological time. As such, in addition to identifying a potentially diagnostic PBS *in situ*, detection of organic matter would be a compelling indicator of priority for further investigation at the site, including caching for return to Earth.

However, the utility of organic matter detection to a search for PBS, however high, is logically separable from a *requirement* to detect organic matter as a prerequisite for sample return, which this mission explicitly avoids levying. This position applies both to (a) the decision to cache any given sample, as well as (b) the mission as a whole.

(a) As a practical matter, it is very possible that a sample may host an organic PBS, and yet be undetectable *in situ*. At a basic level, organics may simply be present at sufficiently low bulk concentrations (say, parts per trillion) and/or isolated to extremely fine spatial scales (say, microns or below) so as to make their *in situ* detection extremely challenging using current flight-ready techniques. In addition, a sample may host an organic PBS that presents a detectable signature, such as organic carbon, while remaining ambiguous in detail without context provided only by resolution of analytical interferences, structural analysis, or spatial/statistical association with other features and/or other types of PBS in the sample. Such features as extremely low LODs, fine spatial scales, subtle structural features (e.g., chirality), compound-specific biases (e.g., isotopes), and resolution of analytical interferences are, for the most part, the sole purview of returned sample analyses as summarized in Table 3-5. Given the present state of knowledge from analyses of martian meteorites and from missions, it would be logical to expect that some samples acquired from a zone of high habitability and possessing high BPP, but missing a clear signal *in situ*, could still host an organic PBS. Moreover such samples may well contain

[6] taphonomic conditions – the conditions leading to the transition (and transformations) of remains, parts or products of organisms from their living state to their fossils in geologic deposits

detectable PBS of any other type. The totality of information available during the mission, which cannot be completely known in advance, would advise the caching selection process. As such it cannot be required in advance that any particular sample, at any point in the mission, be found to contain an organic PBS in order to justify its placement into the return cache.

(b) Logically, then, the mission cannot place an "operational" requirement on the presence of any given PBS in the cache as a whole, and in particular the SDT cannot stipulate conditions for the return of a cache, such as that it must contain at least one core sample with detectable organic matter. Future science teams would make such decisions; here we require only the capability for discovery and documentation within quantifiable bounds. As described in other sections, and as more fully studied elsewhere such as by the MRR-SAG and the Planetary Decadal Survey (NRC, 2011), there are many areas of scientific justification leading to the prioritization of sample return. Detection and full, unambiguous analysis of potential organic biosignatures toward the question of life on Mars could obviously be a central reason, but not the only one.

Finding B-15: Although the capability to detect the presence of organics in candidate samples is a threshold requirement, the actual detection of organics is not a precondition for returning samples to Earth.

Table 3-5. Biosignature analysis will always be better in Earth-based laboratories*. In situ analyses provide a "first cut" at measurements of organics across a number of pertinent factors, both for mission science return and for sample caching triage. Analysis of potential biosignatures remains uncertain and/or ambiguous beyond the in situ figures of merit, while the capabilities of Earth labs have the potential for thorough, unambiguous analyses to extreme levels, and may thereby lead to the resolution of a DBS in a given set of samples.*

Measurement Factor	*In Situ* PBS Analysis	Earth Lab PBS Analysis
Spatial Resolution/ Target Mass or Volume	Wide FOV "bulk" analyses averaging many mineral grains and surfaces. Focused beam analyses down to ~10 mm.	Bulk analyses or individual mineral grains; Focused beam analyses down to < 10 nm.
Sample Preparation	Minimized due to complexity. Abrading, powdering, possible to combine simple reagents.	Abritrarily complex solid (thin section), gas, or liquid extractions and separations.
Limit of Detection	Typically in the ppmw-ppbw range for bulk analysis. Can go lower with extra sample prep.	Can achieve <pptw (10^{-12}) for targeted compounds in small bulk samples or extracts.
Selectivity	Many techniques are broad-band by design, with some ambiguity accepted. Others target selected species with higher sensitivity.	Multiple techniques available to pick arbitrary species out of matrix with a targeted molecular probes or high mass resolution.
Structural Analysis	Possible but limited in scope and possible LOD of compounds.	Molecule structure can be unambiguously identified.
Replicate Analysis	Limited by mission scope, resources, and analytical power.	Arbitrarily high capability; samples can also be archived.
Responsive Analysis	Highly capable as long as follow-up is within mission scope, instrument capability, and rover range. Otherwise, limited.	Extremely capable as long as follow-up analysis is possible with returned samples (limited only by variety collected).

3.3.2 Measurement Options and Priorities

The SDT identified a range of options for measurements required to accomplish tasks related to Objective B. The SDT identified these options without regard to specific instruments or techniques and then prioritized the measurements according to importance. The traceability matrix (Table 3-6) illustrates how the biosignatures-related goals and objectives are related to the desired measurements.

3.3.2.1 Threshold

A detailed description of the first five measurements listed below is given in Section 3.2.2.3. The additional comments here refer more specifically to search for potential biosignatures. In addition, organic matter detection is included here in the threshold set.

3.3.2.1.1 Context Imaging

Section 3.2.2.3 articulates the fundamental ways by which context imaging enables exploration with a focus on conducting geologic field investigations. Particularly relevant for identifying potential biosignatures are observations of both the terrain and the rock outcrops and fabrics that support assessments of past habitable environments and the potential for preservation of biosignatures. One category of biosignature that a context imager might detect directly are rock macrostructures created by biological communities.

Stromatolites and thrombolites are examples of such macrostructures. The specifications required for a context imager to support biosignatures investigations are identical to those specified in Section 3.2.2.3.

3.3.2.1.2 Context Mineralogy

Most relevant are observations of mineral occurrences in the terrain and in rock outcrops that are promising with respect to past habitable environments and the potential for preservation of potential biosignatures. The specifications required for a context mineralogy measurements to support biosignatures investigations are identical to those specified in Section 3.2.2.3.

3.3.2.1.3 Fine-scale Imaging

This investigation would characterize grain morphologies and the textural fabrics of rocks and soils at a microscopic scale. It also could assist in the search for any potential morphological biosignatures. The specifications required for fine-scale imaging measurements to support biosignatures investigations are identical to those specified in Section 3.2.2.3.

3.3.2.1.4 Fine-scale Elemental Chemistry

This measurement would support assessments of past habitable environments and the potential for preservation of biosignatures by detecting evidence of the activity of liquid water (e.g., the mobilization of relatively water-soluble elements) as well as the compositions of chemical species that promote the preservation of biosignatures. One category of potential biosignature that elemental measurements might detect directly would be a spatial variation in elemental abundances that are difficult to explain solely by nonbiological processes. The specifications required to support biosignatures investigations are identical to those specified in Section 3.2.2.3.

3.3.2.1.5 Fine-scale Mineralogy

This measurement supports assessments of past habitable environments and the potential for preservation of biosignatures by detecting mineralogical evidence of the activity of liquid water (e.g., minerals whose formation required the presence of water) as well as the presence of minerals that promote the preservation of biosignatures. Biominerals are a category of potential biosignature that clearly is related to this measurement, but the SDT concluded that the detection of any potential biominerals would probably require Earth-based laboratories. The specifications required for measurements of fine-scale mineralogy to support investigations of biosignatures are identical to those specified in Section 3.2.2.3.

Table 3-6. *Traceability Matrix for Objective B.*

Science Traceability for In Situ Investigations for Objective B: Assess the biosignature preservation potential within the selected geological environment and search for potential biosignatures.

			Relevant *In Situ* Investigations and What Performance Requirements are Driven by Measurement Objectives								Science support
Science Goal	Science objective	Measurement objectives	context imaging	context mineralogy	fine-scale imaging of arm work vol.	fine-scale mineralogy of arm work vol.	elemental chemistry of arm work vol.	organic detection, characterization in arm work vol.	subsurface composition	subsurface structure	rock surface dust/rind removal
Understand potential for biosignature preservation	Determine processes and conditions in the paleoenvironment, and identify mechanisms for formation and preservation of different biosignatures (e.g. early precipitation of favorable minerals, hydraulic concentration of organic matter).	bedding geometry, thickness, contacts, regional architecture	footprint, detectability	footprint, distances	footprint	footprint	footprint			footprint, resolution	
		character & distribution of sedimentary structures	resolution	resolution	resolution	resolution				footprint, resolution	
		chemistry/mineralogy of cements			bandpasses	detectability, resolution	detectability, quality				
		grain size distribution, grain shape, grain composition			resolution	resolution	resolution	resolution			
		minerals present and their residence (clasts, veins, cements, etc)		resolution	footprint, bandpasses	detectability, resolution	detectability, resolution				
		rock textures & fabrics in relation to compositional variations	resolution, bandpasses	resolution	footprint, bandpasses	detectability, resolution	detectability, resolution				
		mineralogy, chemistry & crystal morphology of chemical sediments	resolution, bandpasses	detectability, resolution	resolution, bandpasses	detectability, resolution	detectability, quality				
	Characterize degree, type & timing of diagenetic processes that could have degraded biosignatures (physical alteration, recrystallization, remineralization, aqueous alteration, oxidation, thermal and/or radiolytic alteration)	clay mineral content		detectability, quality		detectability, quality	quality, resolution				
		textures & associated compositional variations, incl permeability	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution	detectability, resolution				
		geometry of altered rocks relative to host unit(s)	footprint	footprint	footprint	footprint	footprint		detectability, resolution	detectability, resolution	
		variations in chemistry/mineralogy of surface & near-surface materials		detectability, quality		detectability, quality	detectability, quality		detectability, resolution	detectability, resolution	
Identify and characterize materials that may contain biosignatures	Detect/characterize lithologies that may host microfossils, microbial organic deposits or mediated textures	character, distribution, context of fine clastics, chert, chemical seds.	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution	detectability, quality				
		texture, morphology, compositional variations in sediments, basalts	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution	detectability, quality				
	Detect & characterize minerals precipitated in situ that could retain chemical proxies for biology	mineralogy and chemistry of fine scale features (cements, grains, coatings)	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution	detectability, quality				
Detect Potential Biosignatures	Recognize minerals w/ potentially biomediated morphology, or in desequilibrium with paleoenv.	Identity and context of authigenic minerals	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution	detectability, quality				
		3D mineral morphology	resolution, bandpasses	detectability, resolution	footprint, bandpasses	detectability, resolution					
	Determine whether organic material is present	organic matter presence or absence in rocks						detectability			
	Recognize stromatolites, frutexites, thrombolites, etc	correlated morphology, mineralogy and texture of sedimentary deposits	footprint, detectability	footprint, resolution	footprint	footprint	resolution				
	Identify variations in lithochemistry that are difficult to explain abiotically	fine scale variations in elemental abundance relative to rock features			resolution, bandpasses		footprint, quality				
Characterize Potential Biosignatures that have been detected	Map distribution of PBS relative to geological features	OM distribution relative to rock textures, structures, composition			resolution	resolution	resolution	detectability, resolution			
		stratigraphic & lateral distribution of morphological PBS	footprint, bandpasses								
	Document assemblage characteristics of potentially biogenic structures,	Spatial variations in composition or physical attributes of OM						detectability, resolution			
		3D shape, textures, composition of morphological PBS, variations relative to paleoenvironmental changes through time and space.	footprint, detectability	footprint, resolution	footprint, bandpasses	detectability, resolution	detectability, quality	detectability, resolution			

3.3.2.1.6 Organic Matter Detection

Acquiring rock samples having organic matter would be a very high priority for MSR scientific objectives. Organic matter constitutes the chemical backbone of living systems and its molecular complexity can harbor substantial amounts of detailed information about ancient environments and potential biosignatures. The objective of this measurement would be therefore to detect the presence of aliphatic or aromatic compounds, either or both at an abundance of $\leq 10^{-5}$ in bulk rock or soil, or at an abundance of $\leq 10^{-2}$ sampling at a scale of 100 μm or smaller in multiple adjacent measurements. For a bulk measurement, the measurement footprint should be 2 cm or smaller; measurements at a grain scale would be desirable, to sample at a scale $\leq$100 μm. Whatever measurement technique would be applied should be demonstrated to tolerate the roughness of a prepared surface, ±0.5 mm over the instrument footprint being measured, and not to create during measurement a level of heating that would destroy the organic signature being sought.

Finding B-16: To make the types of observations required to assess biosignature preservation potential and search for potential biosignatures, as a threshold requirement the Mars 2020 rover should have at least six measurement types:

1. Context imaging
2. Context mineralogy
3. Fine-scale imaging
4. Fine-scale elemental chemistry
5. Fine-Scale Mineralogy
6. Organic Matter Detection

3.3.2.2 Baseline

3.3.2.2.1 Enhanced Organic Matter Characterization

A more detailed *in situ* characterization of any detected organic matter would substantially improve our search for and assessment of potential biosignatures. A baseline mission should add another method that detects attributes of organic matter in ways that complement the attributes detected by threshold method #6 (Finding B-16) and thereby enhance the characterization of any organic components. One approach might be a method that achieves a smaller spatial sampling scale than the bulk measurement in order to resolve grain-scale variations. Alternatively, a second measurement might detect properties of organic matter that are complementary to those detected by the threshold measurement.

Finding B-17: A baseline mission should add another method that detects attributes of organic matter in ways that complement a threshold method of detecting organic matter and thereby enhance the characterization of any organic components.

3.4 Objective C: Demonstrate Significant Technical Progress Towards the Future Return of Scientifically Selected, Well-Documented Samples to Earth

3.4.1 Scientific Foundation

3.4.1.1 Introduction: The Return of Samples to Earth

The return of samples from Mars has long been a high priority for planetary science (e.g., NRC 1978; Bogard et al., 1979). Compelling scientific arguments for Mars Sample Return have recently been documented in a number of important recent committee reports (NRC, 2007; MSS-SAG-2008; ND-SAG, 2008; iMARS, 2008; MRR-SAG, 2010; E2E-iSAG, 2011; NRC, 2011; MPPG, 2012; JSWG, 2012), and the history of thought on the subject is contained in the references therein. While *in situ* and remote measurements have provided numerous important insights into the evolution of Mars, the highest-priority and most-challenging objectives such as precise age-dating and the search for evidence of past life will require the return and subsequent analysis of samples here on Earth.

<u>*The Mars 2020 rover would…*</u>

…enable the enormous leap in Mars science that would come from eventually returning to Earth a storage cache filled with compelling rocks and soils for analysis using the full power of the world's laboratory capability.

One of the most important reasons for returning samples is for biosignature detection. In the astrobiology community, it is widely accepted that definitive identification of biosignatures from Mars would most likely be possible only with returned samples (e.g., MacPherson et al 2001; Beaty et al 2008; ND-SAG 2008; NRC 2007 and references therein). It is extremely unlikely to be possible with *in situ* measurements alone. The identification of biosignatures requires exhaustive testing of alternate hypotheses and integration of multiple lines of carefully acquired evidence. The implications of such a finding are so profound that only the most thorough, careful, state-of-the-art suite of investigations would be sufficient for widespread acceptance of the result. The range of measurements and sample preparation methods that could be practically accommodated on a single rover would be extremely limited. In contrast, with returned samples in hand here on Earth, the full analytical and sample preparation capabilities of terrestrial laboratories could be applied, and the analytical approach could evolve to take advantage of new knowledge (including that gained from the samples) and advances in laboratory instrument technologies. Moreover, it would be possible to run replicate sample analyses in different labs to validate findings. The utility and critical scientific importance of such robust, precise laboratory measurements has been consistently demonstrated by the analysis of meteorites, cosmic dust, and the returned Apollo, Stardust, and Genesis samples over the past four decades.

In recent years, the goals of sample return have shifted significantly in response to what we have learned about Mars and about the habitats for and adaptability of life on Earth. Early justifications for Mars sample return emphasized the need for the samples to reveal details of the geologic evolution of the planet. More recently, though, with an armada of orbiters, landers, and rovers improving our understanding of the role of water in the planet's evolution and of the likelihood of past habitable conditions having existed at and near the surface, the emphasis has shifted toward searching for evidence of life (*e.g.*, NRC 2007; 2011). Indeed, the most recent findings by the MER and MSL rovers of sedimentary rocks containing reducing components, diagenetic clay minerals, and water-deposited veins (Squyres et al 2013; Grotzinger et al., 2013) reinforce these inferences about past habitability and provide solid evidence for biosignature preservation potential. In addition, findings of abiotic macromolecular carbon (with N, O, H) in martian meteorites in general (Steele et al 2012; Grady et. al. 2012), and of abundant water in martian meteorite NWA7034 in particular (Agee et. al., 2013), confirm the availability of compounds needed for life and show that organics could be preserved at and near the martian surface over geologic timescales. These recent findings stress even further the importance of returned samples to investigate whether Mars was ever inhabited by microbial life (see Fig. 3-11).

Finding C-1: Recent scientific findings reinforce the logic leading to the conclusions of the detailed technical and scientific arguments made by the Decadal Survey (NRC, 2011) and MEPAG (most recently summarized in E2E-iSAG, 2012) that returned samples play a critical role in the scientific exploration of Mars.

3.4.1.1.1 Has Anything Changed?

In understanding and justifying the requirements on Mars Sample Return and its precursors, the 2020 SDT has relied heavily on findings and proposals/recommendations from prior studies and reports. It is crucial, then, to examine whether the scientific rationales on which these reports were based are still valid, and still pertain to the proposed Mars 2020 rover mission. The basic rationale for sample return from Mars is essentially unchanged from its first conception in the 1970s (*e.g.,* NRC, 1978; Jones & Treiman 1998):

- Sample return allows the full array of analytical instruments to be applied, without consideration of their needs for power, mass, volume, data rate, or any other constraints that are levied on spacecraft instruments
- Sample return allows analyses beyond those originally conceived, whereas spacecraft analyses are limited to those by instruments as flown
- Sample return allows analyses into the future, by instruments not yet developed and in response to science questions not yet formulated.

None of the discoveries of the last decade have changed this fundamental rationale for Mars Sample Return. If anything, continuing studies on martian meteorites have reinforced the ideas of how much science return could be derived from each small sample in hand (*e.g.*, Filiberto et al. 2011; Agee et al. 2013).

Similarly, our understanding of Mars' geology and history has not changed so drastically as to invalidate the ideas underlying the recent SAG and Decadal reports; in fact, some of the ideas have been reinforced. The last few years have seen a significant elaboration of our understanding and knowledge of Mars, its geology and history, and its potential for habitable environments. Yet, none of these advances invalidate or change the ideas that underlay the earlier conclusions: that although Mars' uppermost surface is now significantly adverse to life (as we know it from Earth), there were times and places in the past where conditions were clement for life, and that rocks representing those times and conditions are exposed at (or near) Mars' surface for investigation. Indications of such potentially clement conditions, particularly the presence of liquid water, are seen from orbit by landscape morphology, and by mineralogy. Landscape features indicative of liquid water include erosional forms like channels (now detectable in the subsurface: Morgan *et al.,* 2013), and depositional forms like deltas and alluvial fans (*e.g.*, in Eberswalde, Holden, Gale, and Jezero craters). Mineralogical indicators of liquid water include water-bearing or water-deposited minerals such as sulfates (Ca-, Mg-, Fe-), phyllosilicates, and halides, which are being found in more and more sites across Mars (*e.g.,* Grotzinger *et al.,* 2011). The presence of halide-rich sediments has been confirmed in the last few years (*e.g.*, Glotch *et al*., 2013). These recent findings all reinforce – rather than change – the inference of past potentially habitable environments.

The recent MRO/HiRISE discovery of recurring slope lineae (RSLs) in the walls of some southern mid-latitude craters (*e.g.,* McEwen *et al.,* 2012) could be signs of present-day release of liquid water. However, understanding of RSLs is still too immature for the SDT to conclude that exploring them *in situ* is more compelling for astrobiology than sample return. Also, their possible "special region" status could place complex and/or costly planetary protection constraints on potential missions to RSLs.

3.4.1.2 What is "Significant Technical Progress"?

To decide what constitutes significant technical progress along the path to the return of samples to Earth, we must first understand the path itself. The return of scientifically-selected, well-documented samples from Mars would require a number of specific functional and technical steps. A mission must (a) launch from Earth and land in an appropriately-selected landing site on Mars, (b) scientifically select and document sample targets,(c) acquire and cache samples from those targets, (d) package and prepare the cache for Earth return, (e) launch the cache from Mars, likely into martian orbit and (f) capture the orbiting cache and return it safely to the Earth. The samples would then have to be retrieved, potentially quarantined, and preserved in such a way that potential hazards are identified and mitigated. Only after all of that has been achieved could the full scientific potential of the returned samples begin to be realized in terrestrial laboratories.

In practical terms, steps (e) and (f) are beyond the currently envisioned scope and resources of the Mars 2020 mission.

Various options could be implemented by the Mars 2020 rover to potentially achieve technical progress toward MSR.

1. Sample acquisition demonstration and assembly of a demonstration cache (*i.e.*, one that would be in some way not returnable).
2. Scientific selection of samples (no acquisition).
3. A cache that would be considered in every respect to be returnable.
4. A MAV demonstration[7]
5. A sample fetch/retrieval demonstration

If the Mars 2020 rover selected sample targets but did not core and cache the samples, then a second follow-on mission would either need to return to the site to actually collect the samples and package them for return, or go to a new site, identify and collect samples there. This follow-on mission would require most, if not all, of the capabilities of the Mars 2020 rover to ensure that the correct/desired materials are acquired (Fig. 3-16). Thus, the net outcome would be that the first mission would need to be largely duplicated by the second, and the first mission would effectively have made little technical progress along the path to MSR. Arguably, that first mission would not represent any more technical progress towards sample return than MSL or MER, and could be more accurately considered an independent *in situ* rover mission.

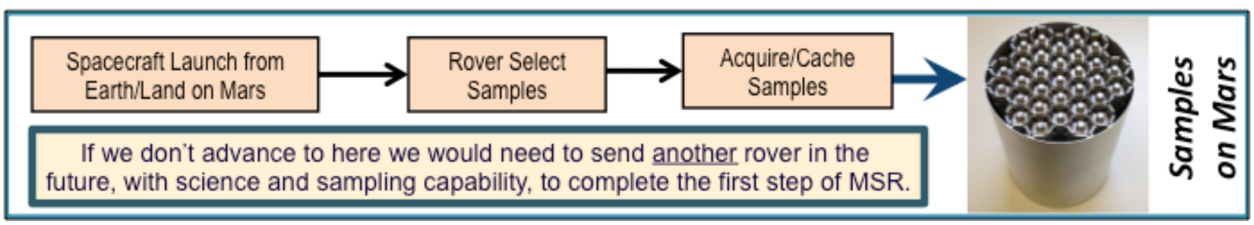


Figure 3-16. Illustration of the first major milestone in returning samples from Mars, which is to have acquired and cached the samples. *In the view of the SDT, the Mars 2020 rover needs to advance at least to this point in order to have achieved "sufficient progress" towards MSR. Image of cache canister courtesy P. Younse.*

The possibility that the first mission (Mars 2020 rover) would have selected samples that would not be scientifically acceptable to return to Earth is unlikely; as discussed by the NRC (2007, 2011), it is widely accepted that we know enough now to be able to select a landing site for which there is a very high probability of being able to assemble a scientifically-compelling suite of samples for future return to Earth. However, that decision is dependent on the future budget picture, and on the other opportunities available to NASA, and an outcome is not assumed by this SDT.

A demonstration of any kind (MAV, fetch and sampling demonstrations) does not complete any of the steps along the path to MSR, they only demonstrate the step. Thus, it would be difficult to consider demonstrations as significant technical progress. Moreover, most aspects of selecting and caching

[7] The Mars Program Planning Group (MPPG) addressed MSR-related technology demonstrations as part of its deliberations in 2012. Therefore, this SDT chose not to repeat the assessment of this type of demonstration.

samples could be validated on Earth. Additionally, in order to be a useful demonstration, any proposed demonstration cache would need to be similar in cleanliness, encapsulation, lifetime, and sample variety to a returnable cache; the technical requirements and cost would be almost as rigorous as those of a returnable cache. Finally, as shown on Figure 3-17, according to MPPG (2012), the additional cost of adding a returnable—as opposed to a non-returnable—cache is a very small part of the total cost of a Mars rover mission. The value of the opportunities created by making the cache returnable far exceed the incremental cost.

Finding C-2: The scientific value of a returnable cache greatly exceeds that of a demonstration cache, at only a small increase in cost.

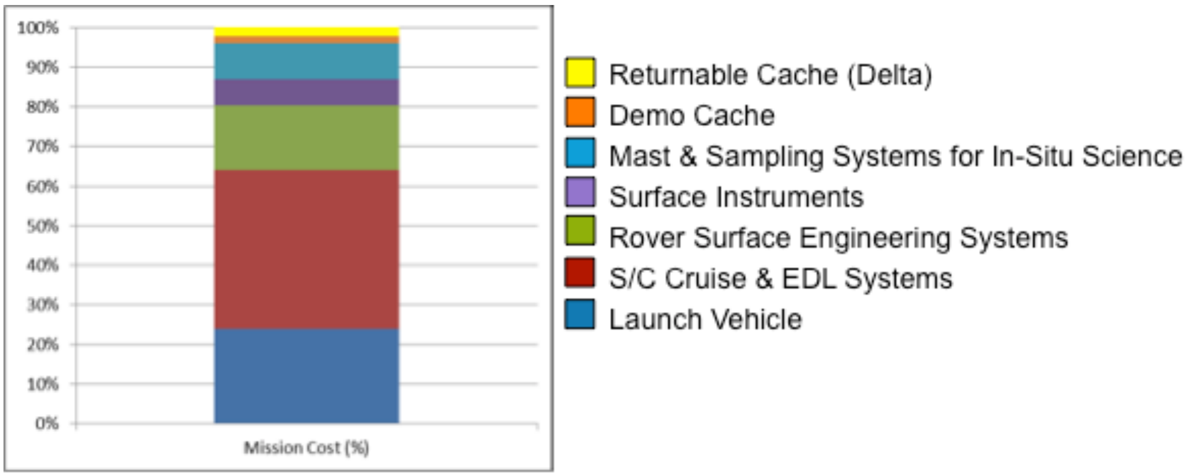


Figure 3-17. The incremental cost of adding a returnable cache to the Mars 2020 rover mission. *The costs in this figure are based on recent Mars 2020 costing work, heavily informed by the MPPG (2012) study, and as-built MSL costs. The planetary protection and contamination control costs would be substantially higher for a returnable cache than a demonstration cache, but for this kind of coarse budget analysis, it is possible to make assumptions that are defensible to within a reasonable error bar. M. Wallace, personal communication, 2013.*

If the Mars 2020 rover selected sample targets but did not core and cache the samples, then a second follow-on mission would either need to return to the site to actually collect the samples and package them for return, or go to a new site, identify and collect samples there. This follow-on mission would require most, if not all, of the capabilities of the Mars 2020 rover to ensure that the correct/desired materials are acquired (Fig. 3-16). Thus, the net outcome would be that the first mission would need to be largely duplicated by the second, and the first mission would effectively have made little technical progress along the path to MSR. Arguably, that first mission would not represent any more technical progress towards sample return than MSL or MER, and could be more accurately considered an independent *in situ* rover mission.

The likelihood that the first mission (Mars 2020 rover) would have selected samples that would not be scientifically acceptable to return to Earth is unlikely; as discussed by the NRC (2007, 2011), it is widely accepted that we know enough now to be able to select a landing site for which there is a very high probability of being able to assemble a scientifically-compelling suite of samples for future return to Earth. However, that decision is dependent on the future budget picture, and on the other opportunities available to NASA, and an outcome is not assumed by this SDT.

Only the identification and creation of a returnable cache would *complete* the initial part of Mars sample return (steps a, b, and c above; see Fig. 3-16). Thus, in order for the 2020 mission specifically to demonstrate significant technical progress toward sample return, it must identify and document samples, *and* cache them in a manner that would allow for eventual return to Earth.

Table 3-7. The greatest progress towards sample return would involve the selection and assembly of a returnable cache*. Possible ways that future missions could achieve technical progress towards MSR*

Options for Technical Progress Toward MSR	New Capability?	Consistent with Proposed Mars-2020 Resources?	Resulting contribution to MSR	
			Reduces Science or Engineering Risk	Achieves Major Milestone
Sample Retrieval/Handoff (Fetch)	Partial	N/A	N/A	
Select Samples & Assemble Demonstration Cache	✓	✓	✓	
Select Samples (for future collection)		✓		
Select Samples & Assemble Returnable Cache	✓	✓	✓	✓

Major Finding C-3: Significant technical progress by Mars 2020 towards the future return of samples to Earth within the mission constraints demands the development and deployment of a sampling and encapsulation system and the assembly of a cache of scientifically selected, well-documented samples packaged in such a way that they could be returned to Earth.

3.4.1.3 Attributes of a Returnable Cache

3.4.1.3.1 Introduction

If significant technical progress towards the future return of samples to Earth requires a returnable cache, then the attributes of such a cache need to be defined. We recognize three attributes that constitute a returnable cache: scientific merit, engineering feasibility, and planetary protection compliance (Fig. 3-18).

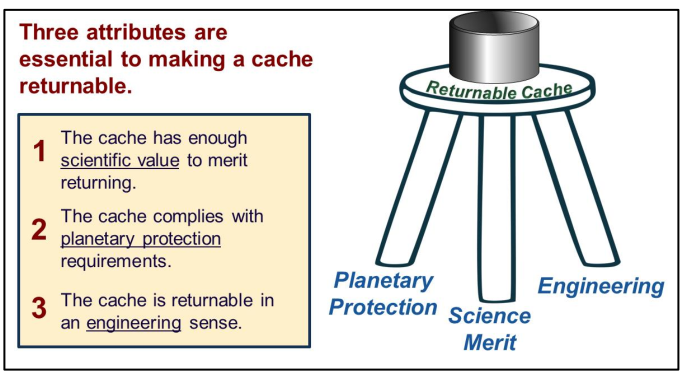


Figure 3-18. A returnable cache is one that has scientific value, complies with planetary protection requirements and meets proper engineering standards.

3.4.1.3.2 Scientific Merit of Samples to be to be Returned

The scientific objectives and priorities of MSR have most recently been formalized by E2E-iSAG (2012). It was chartered in part to consolidate and prioritize a reference set of overall science objectives identified in prior NRC and MEPAG reports, from which the science-related requirements for the individual flight missions of MSR could be derived, and trades between them could be worked. Particular attention was paid to aspects of the sampling mission. Because no new scientific findings alter the logic leading to the conclusions arrived at in its report (Finding C-1), we define the scientific merit of a returnable cache as one with samples collected to achieve the scientific objectives identified by E2E-iSAG (2012; Fig. 3-19).

3.4.1.3.3 Additional Attributes of Scientific Returnability

The most recent Planetary Science Decadal Survey committee concluded (NRC, 2011) that the analysis of carefully selected and well-documented samples from a well-characterized site would provide the highest scientific return on investment for understanding Mars and addressing the question of whether Mars has ever been an abode of life. The SDT agrees with E2E-iSAG (2012) that for the returned samples to have enough science value to significantly advance our understanding of Mars and whether the planet ever harbored life, the samples must meet the following conditions: (1) the field context of the samples must be adequately documented, (2) the samples should be screened from a large set of potential return candidates, (3) each sample must be large enough to support their end use, (4) some of the samples should constitute related suites, (4) the samples should be representative of the geologic diversity of the site sampled, (5) the collection should include some relatively fresh igneous rocks as well as either water-lain sedimentary rocks or hydrothermally altered rocks, (7) the samples should be packaged so as to prevent co-mingling of the different samples, and 8) the samples should not be contaminated with Earth-sourced contaminants (especially organic matter) beyond acceptable levels.

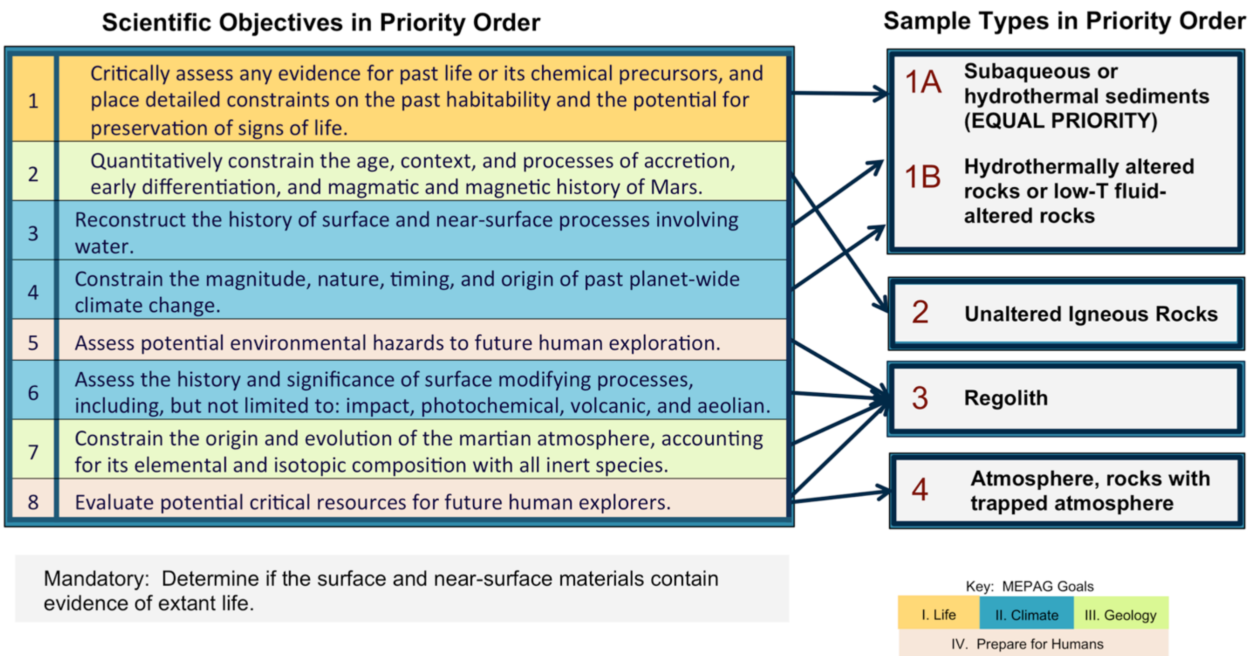


Figure 3-19. Listing of the science objectives proposed for MSR (from E2E-iSAG, 2012). This would lead to picking certain types of samples for caching and future return to Earth.

Finding C-4: A cache that merits returning in a scientific sense is one that has the potential to achieve the scientific objectives of sample return identified by E2E-iSAG (2012).

3.4.1.3.4 Engineering Factors for Cache Returnability

In order for the cache to be returned, it must first be returnable. The notional Mars Sample Return architecture, based on what was articulated to the Planetary Science Decadal Survey (NRC, 2011) and of which the 2020 mission would be part, consists of three missions. The first would be the 2020 mission concept being considered here, if it were to prepare a returnable cache as the SDT proposes (Finding C-3). The second mission would acquire and launch the sample cache into Mars or Solar orbit. The third mission would capture the sample cache in space, and then bring it to the vicinity of Earth and/or land on Earth. A fourth event would be the safe and orderly extraction of the samples from the cache in a sample receiving facility on Earth. In order for the sample cache to be returnable, then, it must be compatible with all of these later missions and activities.

The key return compatibility characteristics of the sample cache are:

1. The mass and mass distribution of the loaded sample cache and its uncertainty

2. The size and shape of the cache;
3. The interfaces and mechanisms that facilitate the extraction of the cache from the (possibly inert) caching system;
4. The interfaces that facilitate the attachment of the cache to the subsequent vehicle; and
5. The ability of the cache (in coordination with the subsequent containment vessels into which the cache would be placed) to preserve the integrity of the samples during the subsequent environments and dynamic events including the wait for the return mission, the launch from Mars, capture by the return vehicle, landing on Earth, and the extraction of the samples from the cache.

Those represent a minimum set of characteristics for the first mission. Other responsibilities are expected to be deferred to subsequent missions. Such deferred responsibilities include the sealing of a container around the cache to collect and contain an atmospheric sample as well as to isolate the samples from the hard vacuum of space, and the assurance this seal would maintain that containment upon return to Earth.

A key difficulty in verifying the engineering returnability of the cache would be that the potential subsequent missions would be at a lower level of design maturity at the time that the Mars 2020 system would qualify for flight. This introduces the risk that the subsequent missions could unknowingly be rendered unaffordable or infeasible by choices made in the design of the Mars 2020 cache. This risk should be mitigated by sufficient investments in proof-of-concept designs for the subsequent missions, with increasing levels of maturity for those portions of the designs closer to the cache interfaces, to the point of developing prototype hardware directly on the other side of those interfaces, and by incorporating prudent margins against the cache size and mass.

To coordinate the development of a returnable cache assembly, the Mars 2020 project should be required to verify before launch that the sample cache complies with a subsequent mission's interface specifications that would be negotiated with the Mars Exploration Program.

3.4.1.3.5 Planetary Protection Factors for Cache Returnability

Finally, all steps in the process of acquisition of samples and their ultimate return to Earth must be conducted so as to conform to planetary protection requirements. For a returnable cache, two types of planetary protection issues pertain (round-trip and back). Round-trip planetary protection refers to protection of the contents of the cache from terrestrial contamination. Since the Mars 2020 mission concept is to assemble a cache of samples with the intent that it would be returned by a potential future return mission, the samples and the associated hardware must be kept free of "round-trip" Earth organisms that could interfere with biohazard and life-detection testing of martian samples upon return to Earth. This requires that the cache container and its associated elements (e.g., sample tubes, sampling bits) be cleaned and maintained in a pristine state. This requirement affects both the design of the caching equipment and its operation on Mars.

Back planetary protection is the protection of Earth from contamination from another planetary body. Of particular concern is the possible uncontained release of Mars material from the returned sample/spacecraft. While this aspect of planetary protection directly pertains to the cache, it is expected that sample containment assurance would be the job of the cache retrieval mission; in other words, the sample return spacecraft would be responsible for isolating the cache from the rest of the spacecraft the Earth.

(For completeness, forward planetary protection is the protection of the visited planetary body from contamination by Earth-sourced organisms. The Mars 2020 mission would need to meet forward planetary protection requirements, but they would be applied at the full spacecraft level without special consideration for the cache.)

Table 3-8. Science Traceability Matrix for Objective C.

Science Traceability for In Situ Investigations for Objective C: Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth											
Source: Table 1 of E2E iSAG			*Revevant In Situ* Investigations and What Performance Requirements are Driven by Measurement Objectives								Science support
Science Goals Addressed by for Documented and cached Samples	Required Geologic Material	Measurement Objective to Identify Material	context imaging	context mineralogy	fine-scale imaging of arm work vol.	fine-scale mineralogy of arm work vol.	elemental chemistry of arm work vol.	organic detection, characterization in arm work vol.	subsurface composition	subsurface structure	rock surface dust/rind removal
A. Life - Critically assess any evidence for past life <u>or its chemical precursors</u>, and place detailed constraints on the past habitability and the potential for preservation of the signs of life	1A. Subaqueous or hydrothermal sediments (includes rocks altered by meteoric water / surface processes)	Preserved evidence suggesting biotic or prebiotic signatures	footprint, resolution, bandpasses	resolution, detectability	footprint, bandpasses	footprint, detectability	resolution, detectability	detectability			
		Morphologic and cmpositional evidence for paleoenvironments	footprint, resolution, bandpasses	resolution, detectability	footprint, bandpasses	footprint, detectability	resolution, detectability		detectability, resolution	detectability, resolution	
	1B. Rocks altered by hydrothermal or low temperature fluids	Mineral/ textural characteristics consistent with PBS, energy source, or preservation	resolution, bandpasses	resolution, detectability, quality	footprint, detectability	footprint, detectability	resolution, detectability	detectability, resolution			
		Variations within a hydrothermal system, such as water/rock ratio, T, fluid chemistry.	resolution, bandpasses	resolution, detectability	footprint, bandpasses	footprint, detectability	detectability, quality		detectability, resolution	detectability, resolution	
B. Surface - Reconstruct the history of near-surface processes involving water.	1A. Subaqueous or hydrothermal sediments	Stratigraphic position spanning climate change	footprint, bandpasses	footprint, detectability	footprint, bandpasses	footprint, detectability	detectability		detectability, resolution	detectability, resolution	
		Elemental or mineralogic compsition constraining chemistry of ancient waters	bandpasses	detectability, quality	bandpasses	resolution, detectability, quality	detectability, quality		detectability		
B. Surface - Assess the history and significance of surface modifying processes, including, but not limited to: impact, photochemical, volcanic, and aeolian. Constrain the magnitude, nature, timing, and origin of past planet-wide climate change.	2. Unaltered Igneous Rock (in this case a volcanic unit with known stratigraphic age)	Rocks preserve primary igneous character least affected by alteration, weathering, or impact	bandpasses	detectability, quality	bandpasses	detectability, quality	detectability, quality				
		Rocks that span variations in bulk composition		detectability, quality		detectability, quality	detectability, quality		detectability		
		Rocks with glassy texture due to quenching	resolution, bandpasses	resolution, detectability	bandpasses	resolution, detectability					
	1A. Subaqueous or hydrothermal sediments (likely included would be rocks altered by meteoric water or surface processes)	Morphologic and mineralogic evidence for paleoenvironments	resolution, bandpasses	resolution, detectability, quality	footprint, bandpasses	resolution, detectability				detectability, resolution	
		Variations within a hydrothermal system, such as water/rock ratio, T, fluid chemistry.	resolution, bandpasses	resolution, detectability	footprint, bandpasses	footprint, detectability	detectability, quality		detectability, resolution	detectability, resolution	
		Stratigraphic position spanning climate change	footprint, bandpasses	footprint, detectability	footprint, bandpasses	footprint, detectability	detectability		detectability, resolution	detectability, resolution	
	3. Regolith (including airfall dust, surface soil and shallow subsurface)	Airfall dust grain size and mineralogy	bandpasses	detectability, quality	bandpasses	detectability, quality					
		Sand or dust having various compositions including mobile vs. indurated	resolution, bandpasses	resolution, detectability	resolution, detectability	resolution, detectability	detectability, quality		detectability, resolution		
		Salt concentrations or efflorescences	resolution, bandpasses	resolution, detectability	resolution, bandpasses	resolution, detectability	resolution, detectability, quality			detectability, resolution	
		Duricrust or ferricrete	resolution, bandpasses	resolution, detectability	resolution, bandpasses	resolution, detectability	resolution, detectability, quality			detectability, resolution	
		Material consistent with impact or devitrified glass	resolution, bandpasses	resolution, detectability	resolution, bandpasses		resolution, detectability				
C. Planetary Evolution - Constrain planetary age, accretion, early differentiation, magmatic and magnetic history	2. Unaltered Igneous Rock (in this case a volcanic unit with known stratigraphic age)	Noachian rocks w/ known stratigraphic context, orientation to measure paleomagnetic field	bandpasses	detectability, quality	bandpasses	detectability, quality	resolution, detectability, quality				
		Rocks of Hesperian / Amazonian age	footprint	detectability		detectability					
		Rocks that contain xenolithic clasts	resolution, bandpasses	resolution, detectability	footprint, bandpasses	resolution, detectability	resolution, detectability, quality				
C. Planetary Evolution-Origin/evolution of atmosphere	4. Atmospheric gas sample	NOT REQUIRED OF THIS MISSION									
D. Human - Assess environmental hazards	3. Regolith (including airfall, soil and shallow subsurface)	Presence of toxic elements					detectability, quality				
		Presence of toxic minerals		detectability, quality		detectability, quality					
D. Human - Evaluate potential resources	Water bearing materials	Regolith content of H2O		detectability, quality		detectability, quality	detectability, quality		detectability		

Formulation of the standards and procedures needed to meet these various planetary protection requirements is outside the charter of this SDT. It will be the responsibility of the planetary protection officer and other national and international groups specifically chartered for that task.

3.4.2 Measurement Options and Priorities

The overall strategy to find samples and place them into context has requirements similar to those to investigate habitability. A first tier of landed measurements documents the site and locates potential materials for sampling; a second tier investigates potential samples in further detail, sufficient to support a decision to sample or not, and to characterize the lithology being sampled. The threshold instrument suite for MSR sample collection objectives contains five investigations: a contextual imaging system; a contextual mineralogy investigation; and a close-up microscopic imager, a mineralogy instrument, and a fine scale elemental chemistry analyzer. A baseline suite extends these capabilities to include detection of organic material, which would be a high priority for sampling. Table 3-10 shows how the measurements can be traced back to science objectives and goals. The five threshold measurements are identical to those required for Objectives A and are included in the threshold list for Objective B. These investigations follow closely from previous proposals by E2E-iSAG (2012) and JSWG (2012) (see Table 3-9).

<table>
<tr><th>ND-SAG
(2008)</th><th>MRR-SAG
(2009)</th><th>E2E-iSAG
(2011)</th><th>Decadal Survey
(2011)</th><th>MPPG
(2012)</th></tr>
<tr><td>Color stereo imagery</td><td>Color stereo imagery</td><td>Color stereo imagery</td><td>Pancam</td><td>Color stereo imagery</td></tr>
<tr><td rowspan="2">Mineralogy</td><td>Remote mineralogy</td><td>Remote mineralogy</td><td>NIR Spectrometer</td><td>Remote mineralogy</td></tr>
<tr><td>Close-in Mineralogy</td><td>Close-in Mineralogy</td><td rowspan="2">Dual Wavelength Raman/ Fluorescence Instrument</td><td>Contact Mineralogy</td></tr>
<tr><td>Organic carbon detection</td><td>Organic carbon detection</td><td>Organic carbon detection</td><td></td></tr>
<tr><td>Microscopic imagery</td><td>Microscopic imagery</td><td>Microscopic imagery</td><td>Microscopic imagery</td><td>Microscopic imagery</td></tr>
<tr><td>Bulk Elemental abundance</td><td>Bulk elemental abundance</td><td>Bulk elemental abundance</td><td>Alpha-Particle X-Ray Spectrometer (APXS)</td><td>Bulk elemental chemistry</td></tr>
<tr><td></td><td>Paleomagnetic context</td><td></td><td></td><td></td></tr>
<tr><td></td><td>Age dating</td><td></td><td></td><td></td></tr>
</table>

Key
Required
Desired

Table 3-9. Five previous reports agree that the same threshold set of measurements are required to collect samples for caching. *The measurements needed to carry out scientific selection and proper documentation of context for samples to be used to achieve the scientific objectives of MSR has been considered in detail by five recent planning teams*

3.5 Objective D-1: Provide an Opportunity for Contributed HEOMD Participation, Compatible with the Science Payload and Within the Mission's Payload Capacity

3.5.1 Foundation

> *The Mars 2020 rover would…*
>
> *…play a key role in preparing for the future safe human exploration of the surface of Mars.*

In order to prepare for future human missions, system and mission planners desire data that characterize the environments, identify hazards, and assess resources. Recent, currently operating, and future science missions are invaluable resources for providing these data. The knowledge developed from these data will inform the selection of future landing sites, inform the design new systems, and reduce the risk associated with human exploration. While some data can be obtained through ground-based activities, other data can only be gained in space by remote sensing, *in situ* measurements or sample return. In turn, much of the information desired by human mission planners is also of interest to the science community.

The NASA Human Exploration and Operations Mission Directorate (HEOMD) develops new capabilities for human spaceflight to enable missions to cis-lunar space, near-Earth asteroids, and ultimately to Mars and it moons. The planning of human missions is informed by a set of Strategic Knowledge Gaps (SKGs) that represent the unknown environments, hazards, and the availability of resources at potential destinations that could impact the design of flight systems and human exploration architectures. The SKGs are the basis for HEOMD's investment strategy for robotic precursor missions to acquire this strategic knowledge. Science-focused missions such as Mars 2020 provide valuable and timely measurement opportunities to fill high priority SKGs. Furthermore, obtaining data to satisfy the SKGs in the early 2020s is necessary to support the 2010 National Space Policy of sending humans to Mars in the mid-2030s, which is also consistent with the findings of the 2012 Mars Program Planning Group findings.

The SKGs were initially defined by asking mission planners what types of information they would need about a destination to ensure a safe and successful human mission. The draft SKGs were then reviewed, refined, and prioritized by three independent groups that represent the external science and exploration communities: the Lunar Exploration Analysis Group, the Small Bodies Assessment Group, and the Mars Exploration Program Analysis Group (MEPAG). The International Space Exploration Coordination Group is also integrating the SKGs across the potential destinations to establish a set of prioritized SKGs that is agreed upon internationally, and they will be incorporated into the Global Exploration Roadmap.

The MEPAG formed a focused team called the Precursor Strategy Analysis Group (P-SAG) to further refine and prioritize the SKGs for Mars (P-SAG, 2012). These SKGs fall into three broad classes:

1. **Architecture Drivers**, which are measurements and technology demonstrations that allow missions and systems to be designed more efficiently. These include identification of resources for *in situ* resource utilization (ISRU) to reduce the mass of propellants and other consumables that must be launched from Earth, and knowledge of atmospheric density and winds to design entry, descent, and landing systems.
2. **Crew Safety**, which are measurements of environments and hazards needed to keep the crew safe. These include knowledge of the interplanetary and surface radiation environment, biohazards from possible extant life, and toxicity of materials such as dust that could affect human health.
3. **Operational**, which are measurements to ensure safe operations of systems. These include surface hazards at the landing site, the effects of dust on rover traverse and space suits, forward planetary protection to avoid contamination of special regions on Mars by organisms from Earth, and electrical properties of the atmosphere and the surface that may cause electrostatic discharges that could damage electronics.

Finding D-1: There are three classes of environmental measurements needed to support HEOMD long-term objectives: (1) Architecture Drivers, (2) Crew Safety, and (3) Operational.

3.5.2 Measurement Options and Priorities

To define candidate payloads for the Mars 2020 mission, HEOMD formed a team of subject matter experts to review the results of the PSAG and Mars Program Planning Group (MPPG) studies. The subject matter experts represented the main areas in the three categories of SKGs outlined above. This HEOMD Instrument Team (HIT) identified high priority SKGs that will not be addressed by current or planned Mars missions. The HIT then defined notional instrument concepts or technology demonstrations to address the remaining SKGs (Table 3-10). To the greatest extent possible, the HEOMD instrument concepts were derived from similar instruments that have flown on past missions. Candidate technology demonstrations were based on prototype systems being developed by HEOMD and the NASA Space Technology Mission Directorate (STMD).

Table 3-10. A wide variety of HEO instruments and technology demonstrations were considered for inclusion in the Mars 2020 mission *Candidate HEOMD Instruments and Technology Demonstrations*

Instrument/Demo	Purpose	SKG Addressed	P-SAG Priority	HAT Priority	Comments
MEDLI+	Measure temperatures & pressures on heat shield during EDL	A2-1: Atm. modeling	H	H	MEDLI+ would obtain data on afterbody & lower in atmosphere than MSL
Surface weather station	Measure pressure, temperature, humidity, & winds to validate atmospheric models	B1-2: Local weather B1-3: Surf winds	H, M	H	Complements weather stations on MSL & InSIGHT. Includes wind direction.
Biomarker detector system	Detect biomarkers present in Earth life (e.g., DNA, large biomolecules) that might also be components of Mars life at concentrations relevant to contamination limits for possible Mars sample return	B2-1: Biohazards B5-3: Planetary protection	H, M	H	Demonstrate detection of microbial contamination for future human missions; possible detection of Mars life
O2 production from atmosphere	Collect atmospheric carbon dioxide. Analyze dust (size, shape, number) during CO2 collection. Produce small quantities of oxygen and analyze its purity (option).	B6-1: Atm. ISRU B4-2: Dust properties	H	H	Reduces risk for human missions and possible Mars sample return
Neutron directionality	Secondary neutrons from atm. & surface	B3-1: Radiation	M	M	May be able to determine neutron directionality from existing DAN and RAD data
High energy radiation detector	High energy galactic cosmic rays at surface	B3-4: Radiation	M	M	Higher energy range than RAD on MSL
Sterilization experiment	Reduce bioburden on hardware in Mars conditions	B5-3: Planetary protection	M	M	Demonstrate sterilization techniques for future missions
Soil Water extraction	ISRU demo	D1-2: Water resources	M	M	Demonstrate extraction and use of water from surface materials
Atmos. dust size distribution	Dust column abundance	B6-2: Atm. ISRU	L, H	M	May be integrated with atmospheric O_2 production
	Particle shape/size distribution	B6-1: Dust Properties			
Dust toxicity	Assess risk to crew from ingested dust	B3-5: Dust toxicity to crew	M	M	Detect small particles and hazardous chemicals (perchlorates)
Electrometer	Atmospheric electricity conditions	B1-5: Atm. electricity	L	L	Understand the risks to ascent vehicles, ground systems, & human explorers
Landing site selection	Demo selection for human missions using Mars 2020 process	B7-2: Landing site hazards	M	L	Apply human landing criteria to the landing site selection process

A wide range of candidate instruments and technology demonstrations were examined, along with the SKGs that they address and the corresponding priorities assigned by the P-SAG. The Human Spaceflight Architecture Team (HAT), which formulated the Mars 5.0 Design Reference Mission and identified needed mission-enabling capabilities, also assessed the priorities of the candidate payloads. In some cases, the HAT priorities differ from the P-SAG priorities because HAT is considering the SKGs from a crew safety and mission risk perspective. Both sets of priorities were used together to determine overall priorities.

3.5.2.1 Prioritization Criteria for Candidate Payload Evaluation

After prioritizing the candidate payloads with respect to the SKGs and determining which payloads could be ruled out due to cost and operational constraints, the HIT defined additional criteria to rank the remaining payloads. The following prioritization criteria were used:

- Addresses high priority Strategic Knowledge Gaps
- Enabling technology for human Mars exploration architectures and consistent with the National Space Policy
- Synergistic with Mars 2020 science objectives
- Synergistic with MEPAG science objectives
- Spacecraft resource requirements (mass, volume, power)
- Implementation risk (TRL)
- Cost (L: <$10M, M: $10M-$25M, H: >$25M)
- Potential co-funding from other organizations

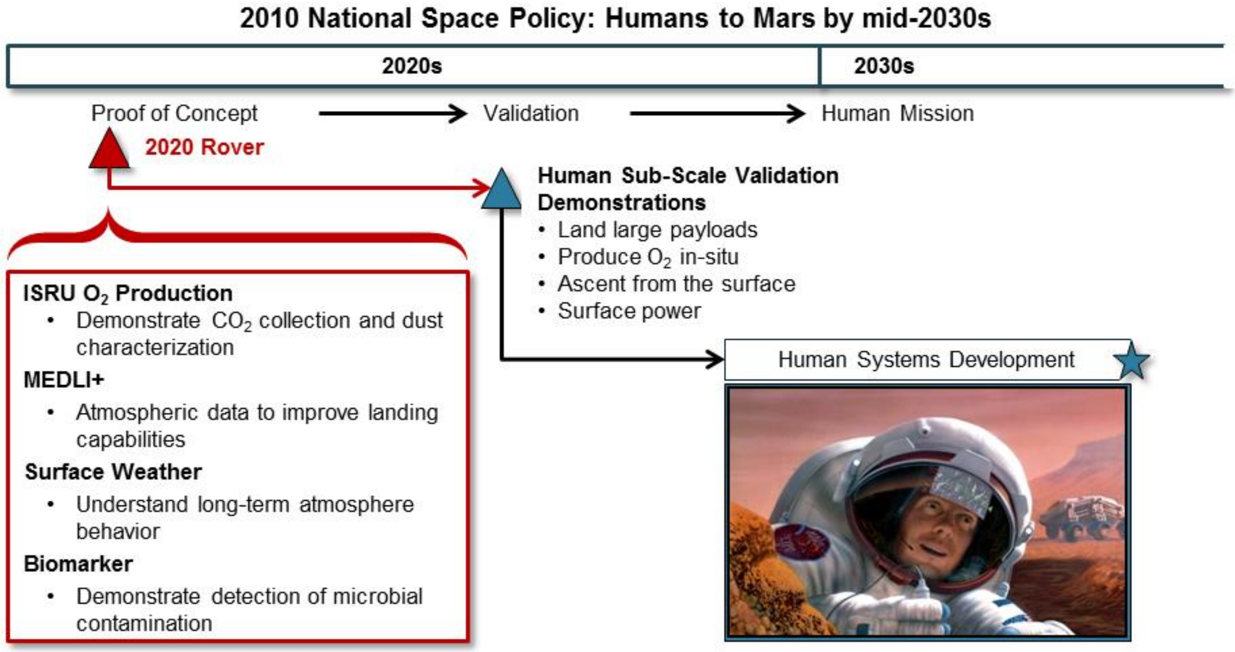


Figure 3-20. Data on ISRU and atmospheric state will help guide HEO high-level planning. *Early demonstration of critical technologies, as well as the gathering of environmental data, are key to potential future human exploration missions to Mars. The 2020 rover mission provides the opportunity to demonstrate environmental effects such as air-borne dust, on the acquisition of CO_2 from the atmosphere. These early data would feed-forward to larger technology validation and systems necessary for potential future human missions to the surface of Mars.*

Table 3-11 summarizes the application of the prioritization criteria to the set of candidate payloads. Each criterion was assigned a value of Low, Medium, or High for a particular payload. The overall payload ranking was determined by aggregating the values of all criteria.

Table 3-11. Overall priority of instruments/demos was generated from a set of common criteria*. HEOMD Payload ranking using prioritization criteria. See Section 9.2.1.*

Instrument/Demo	SKG Priority	Architecture Enabling Tech	Science Synergy w/M2020	Science Synergy w/MEPAG	S/C Resources	Risk	Cost	Co-Funding	Overall Priority
MEDLI+	H	Y	L	M	L	L	M	STMD	2
Surface weather station	H	N	L	H	L	L	M	N	3
Biomarker detector system	H	N	L	M	M	M	M	Intl. Partner	3
Atmospheric ISRU demo - CO2 capture + dust	H	Y	M	M	M	M	M	STMD	1
Atmospheric ISRU demo - CO2 capture + O2 production	H	Y	L	M	H	M	H	STMD	4

The 2010 National Space Policy specifically states that NASA should "[b]y the mid-2030s, send humans to orbit Mars and return them safely to Earth." Although surface missions are not specifically addressed in the Space Policy, understanding the linkages between potential initial orbital missions and subsequent surface missions is necessary for strategic guidance. That is, future human missions to Mars orbit should feed forward to surface missions. HEOMD continues to use potential human missions to the surface of Mars as the key strategic destination to drive technology development, sub-scale demonstrations, and closure of key strategic knowledge gaps. In order to ensure strong technological and programmatic linkage between potential orbital and surface missions, it is viewed that the surface missions should closely follow the preceding orbital missions. As shown in Figure 3-20, the Mars 2020 rover mission would provide a key strategic opportunity to demonstrate key proof-of-concept technologies and gather environmental data to help close key strategic knowledge gaps. These data would be necessary to fold into future larger sub-scale validation demonstrations prior to final commitment to the design and development of the actual human mission vehicles and systems.

3.5.2.2 ISRU

The highest priority HEOMD payload is the demonstration of CO_2 capture and dust size characterization for atmospheric ISRU (Fig. 3-21). This payload addresses two high priority SKGs: demonstrating atmospheric ISRU and measuring dust properties. It would be an architecture enabling technology for human missions to Mars, which likely will depend on ISRU for producing the propellants needed for the return trip to Earth; ISRU can greatly reduce mass transported to the martian surface. As a matter of course, Mars carbon dioxide can be acquired at all locations on Mars with technologies similar to life support. ISRU would demonstrate dust filtration and non-intrusive measurement during Mars carbon dioxide (CO_2) capture and subsequent CO_2 collection via CO_2 freezing with a secondary option to incorporate a rapid-cycle adsorption pump. The proposed ISRU proof-of-concept technology demonstrator, as shown in Figure 3-21, could be run on a non-interference basis with the remainder of the Mars 2020 rover instruments. STMD has agreed to co-fund development of this proposed payload, which reduces the cost to HEOMD, and may allow additional payloads to be flown.

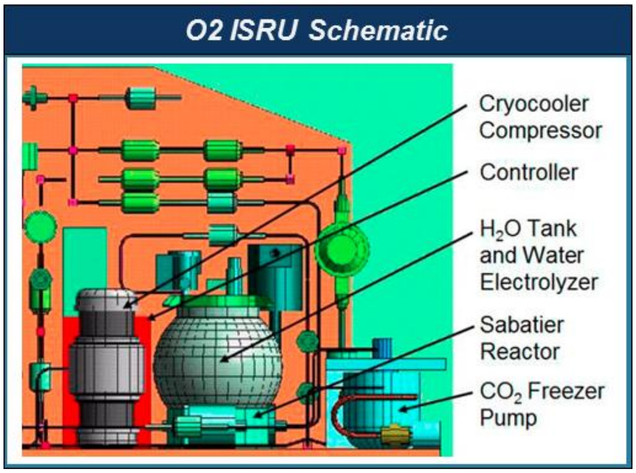


Figure 3-21. Drawing showing components of an ISRU experiment. *Demonstration of the collection of CO_2 and production of oxygen from the atmosphere is an enabling technology for future human exploration of Mars. Demo could be run on close to a non-interference basis with science operations. From G Sanders, personal comm., 2013.*

Understanding the data returned from an ISRU demonstration on Mars relies on also understanding the dusty Mars atmosphere and the diurnally and seasonally varying Mars climate. Dust abundance, particle shape, size and density of the actual environment must be characterized to test and improve filter designs. Such information would be also needed to improve calculation of atmospheric and surface radiation.

Since an ISRU demonstration would occur at a single site, the environment would need to be characterized to assess whether the ISRU results are likely to be representative of other locations. Measurements of surface winds would indicate whether dust in the atmosphere above the site could be injected locally and from which local sources. Mechanisms of local dust mobilization (e.g., by slope winds or by dust devils) can be deduced from local wind, pressure and temperature measurements. More distant sources of dust supplied through atmospheric fall-out from hazes produced by regional or even planet-wide dust storms can be inferred from local pressure measurements. The particle properties of dust from these different sources are expected to be significantly different (e.g., local dust raising will involve larger particles than atmospheric fall-out from distant sources). Finally, humidity measurements, augmented with pressure and temperature data, will constrain the nature of water as a trace contaminant in the freezing process.

3.5.2.3 MEDLI+

The second highest priority HEOMD payload would be a reflight of an enhanced MSL Entry, Descent, and Landing Instrumentation (MEDLI+) payload to acquire temperature and pressure measurements on the heat shield and afterbody. (See Section 3.6.2.4) The temperature and pressure measurements on the heat shield and afterbody during atmospheric entry would be used to validate analytical models for designing future entry, descent, and landing (EDL) systems. EDL systems capable of landing large payloads on Mars are an architecture enabling technology for human missions. STMD may provide co-funding for this proposed payload.

3.5.2.4 Surface Weather Station

The inclusion of a Surface Weather Station on the Mars 2020 payload would provide density for EDL and ascent profiles, plus validation data for global atmosphere models that would enable validation of global model extrapolations of surface pressure. It would also provide local-surface and near-surface validation data for mesoscale and large eddy simulation models in order to validate regional and local model atmospheric conditions.

One concept for a Surface Weather Station is a REMS follow on for pressure, temperature, winds, humidity, as well as a deck or mast-mounted, upward looking Mini-TES or MCS like instrument for vertical temperature profiles. Additionally, a camera with sun filters for total atmospheric aerosol content would be incorporated as well as a LIDAR for aerosol profiles.

The set of environmental characterizations described above could be provided by the surface meteorological package also described as a HEOMD priority. This same set of instrumentation, plus the characterization of the dust properties provided as part of the ISRU demonstration, also would address a number of climatological science questions and objectives. To address the science questions more completely may require more sensitive and more frequent measurements (e.g., flux measurements in addition to field data), but significant progress could be made with instrumentation scoped by the ISRU demo needs. The potential cost impact to the atmospheric ISRU demonstration is expected to be minor.

3.5.2.5 Biomarker Detector System

A “biomarker detector” system could serve two purposes:

1. to determine if martian environments contacted by humans are free of biohazards that might have adverse effects on the exposed crew, and on other terrestrial species if uncontained martian material would be returned to Earth.
2. To determine the extent to which terrestrial contaminants introduced at a possibly inhospitable landing site could be dispersed into more hospitable sites.

An example biomarker detector system is a payload known as “Signs of Life Detector (SOLID)”, which has been developed to detect extant life in planetary bodies. The sample processing involves solvent extraction of molecular biomarkers by means of sonication in the Sample Preparation Unit (SPU). Measurement would be based on fluorescent antibody microarray technology in the Sample Analysis Unit (SAU). SOLID has the capability to interrogate for more than 500 molecular biomarkers in a single assay, starting from a particulate sample (soil, sediment or ice), and has proven sensitivities down to 1-2 ppb (ng/mL) for peptides and proteins, and 10^3-10^4 cells or spores per mL. SOLID could be used for extraterrestrial life detection by targeting universal biomarkers such as amino acids, polymers, polysaccharides, whole cells and microbial spores, and also for planetary protection to monitor forward contamination during robotic/human operations in an extraterrestrial environment.

Integration of the HEOMD instruments, including compatibility with the expected resource constraints of the rover (mass, power, volume, unique integration capabilities), was an important consideration in the instrument selection process. As discussed in Section 9.2.1, assessments indicated that integration of the Biomarker Detection System would not be compatible with the expected rover resources, and thus this potential HEOMD instrument was removed from further consideration as a potential payload by the SDT.

Finding D-2: The three highest priority HEOMD payloads would be ISRU, MEDLI+, and a surface weather station.

3.5.2.6 Summary

HEOMD has defined candidate payloads that address high priority Strategic Knowledge Gaps for human exploration of Mars, that are synergistic with MEPAG and Mars 2020 science objectives, and that can be jointly developed with STMD to demonstrate architecture enabling technologies.

The CO_2 capture and dust characterization payload is HEOMD's proposed contribution to the Mars 2020 mission. It would be the threshold (Priority 1) human exploration payload that addresses Mission Objective D. By incorporating dust characterization and weather measurements, the payload also addresses synergistic science objectives.

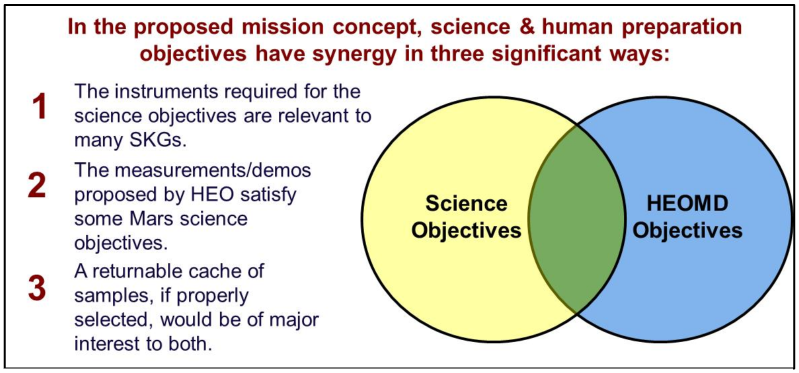


Figure 3-22. There are significant overlaps between the HEO goals and the SMD goals.

MEDLI+ is HEOMD's proposed baseline (Priority 2) payload for Mission Objective D. It may be flown in addition to the atmospheric ISRU demonstration if sufficient co-funding from STMD can be obtained.

These candidate payloads may provide synergistic measurements to address both science and exploration objectives (Fig. 3-22). The HIT worked with the Mars 2020 SDT to determine which HEOMD measurements address MEPAG science objectives, and how the proposed science measurements address HEOMD SKGs. The SDT also assessed how returned samples could address the SKGs so that measurements that can be done with greater precision in ground-based laboratories may be deferred until a later sample return mission.

<u>How HEOMD measurements address MEPAG science objectives</u>

There is considerable overlap between the HEOMD objectives and the MEPAG science objectives. Meeting both sets of objectives requires a better understanding of Mars and the martian environment. Table 3-12 shows how the top priority measurements that address HEOMD strategic knowledge gaps also address MEPAG science objectives.

MEDLI+ and the surface weather station relate to understanding the martian atmosphere to inform the design of entry, descent, and landing systems for large payloads. Understanding the atmospheric density and winds are the key measurements for human exploration, but are also important for science. For example, MEPAG Goal II.1.iii suggests studying the planetary boundary layer to understand how "thermal variation between the surface and the atmosphere combined with mechanical interactions between the wind and surface roughness element drives turbulence." The surface weather station would be of the highest interest to science, though not to the specific science objectives of the Mars 2020 mission. A network of surface weather stations has been a high priority request from the Mars atmosphere community for decades, and a surface weather station is included in the MSL payload. The MEDLI investigation would not be a high priority for science, but it does provide a useful check of the atmospheric models.

Table 3-12. How HEOMD measurements would address MEPAG science objective

Instrument / Demo	MEPAG Science Goals Addressed (2010 version)
Oxygen production from atmosphere	Depends on how the demo is configured, but there is potential for significant progress in understanding the martian dust cycle (Goal II, Objective A).
MEDLI+	**Goal II Objective A: Characterize Mars Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration** *Minor contribution to understanding the Martian atmosphere from EDL measurements.*
Surface Weather Station	**Goal II Objective A: Characterize Mars Atmosphere, Present Climate, and Climate Processes Under Current Orbital Configuration** *Surface weather stations extend our understanding of the atmosphere, especially if linked to measurements from orbit.*

Major Finding D-3: The top-priority measurements that address HEOMD strategic knowledge gaps also benefit Mars science.

How Mars 2020 science measurements would address HEOMD objectives

Measurements that address Objectives A, B, and C have complimentary applications to HEOMD SKGs. The science measurements of context and fine scale imaging, context and fine scale mineralogy, and fine scale elemental chemistry would provide information relevant to understanding dust effects on engineered systems, landing sites and potential hazards at those sites, and potential mineral resources at the martian surface. In addition, the rover mobility system would provide information on ability to drive, and could also be used for trenching experiments to understand the structure of the regolith.

The main measurements addressing science objectives A, B, and C are similar to the measurements made on the MER rovers and the same type of capability exists on the MSL rover. They are not new measurements, but instead provide similar geologic understanding of Mars at an additional location. Similar knowledge gained from the MER and MSL rovers has already significantly retired some risk for human missions to Mars. In particular, the five measurements common to all science objectives (context imaging, context mineralogy, fine-scale imaging, fine-scale mineralogy and fine-scale elemental chemistry) contribute towards understanding dust effects on surface systems, landing sites and hazards, and the availability of resources.

Finding D-4: Measurements that address Objectives A, B, and C have complimentary applications to HEOMD Strategic Knowledge Gaps.

How returned samples would address HEOMD objectives

Returned samples would address the HEOMD objectives related to biohazards, dust properties and toxicity, and regolith chemistry and mineralogy (Table 3-14). One of the key goals of Mars sample return would be analysis for evidence of life, both past and present. The analysis of returned samples may complement *in situ* biomarker measurements to provide greater understanding of potential martian biohazards.

Returned samples of regolith and atmospheric dust would provide detailed information on the dust and regolith properties relevant to the potential impacts on the astronauts and on systems designed to operate in the martian environment. In addition, the detailed chemistry that can be done on Earth would address the question of dust toxicity. Analysis of the regolith and returned rock cores would provide information on chemistry and mineralogy, addressing potential resources on the martian surface.

Table 3-13. How returned samples would address HEOMD objectives

MEPAG Sample Measurements (MEPAG 2010)	HEOMD Objectives Addressed (P-SAG 2012)	Fully (F) or Partially (P) Addressed
Goal I: Analysis for evidence for life	B2-1: Biohazards	F
Goal II A1: Dust particle shape and size distribution Goal II A3	B6-1: Dust properties	F
Goal I B.2: Dust chemistry and mineralogy down to the individual grain level	B3-5: Dust toxicity B4-2: Dust properties	F
Goal II A: Evolved gas analysis on regolith	B7-1: Regolith properties	P
Goal III A.1: Regolith flow measurements	B7-1: Regolith properties	P
Goal III A.1: Regolith particle shape & size distribution	B7-1: Regolith properties	P
Goal I B.2: Detailed mineralogy and chemistry Goal III A.4	D1-3: Hydrated mineral compositions	F

Finding D-5: Returned samples would address the HEOMD objectives related to biohazards, dust properties and toxicity, and regolith chemistry and mineralogy.

3.6 Objective D-2: Provide an Opportunity for Contributed Space Technology Program (STP) Participation, Compatible with the Science Payload and Within the Mission's Payload Capacity

3.6.1 Foundation

NASA's Space Technology Mission Directorate (STMD) rapidly develops, demonstrates, and infuses revolutionary, high-payoff technologies through transparent, collaborative partnerships, expanding the boundaries of the aerospace enterprise. (Note that STMD is referred to by its previous name, STP, in the SDT charter.) This section describes the assessment and prioritization of space technology investments appropriate for the Mars 2020 mission.

The consideration of technology investment opportunities for Mars 2020 is focused on developments that bring high-payoff technologies to the point that a flight project could adopt them with acceptable development risk, and on measurement opportunities that could benefit future technology developments. STMD expects that such investments would be co-funded with other organizations in order to engage the eventual beneficiary in the developments. In the case of Mars 2020, those partners would be HEOMD and SMD. The benefits may be realized on the Mars 2020 mission itself, or in later Mars surface missions, either robotic or crewed.

The Mars 2020 rover project would…

…develop and apply technologies that would enable dramatically improved and more cost-effective future robotic and human exploration of Mars, as well as other solar system targets.

The high payoff benefits of the developments considered fall into these areas:

- Improved landing site access
  - Precision and pinpoint landing
  - A priori and real-time hazard avoidance
  - Increased landing altitude
  - Increased landed mass
- Improved surface mission resources and efficiency
  - Faster mobility
  - Increased autonomy
  - Increased payload energy
  - Increased payload volume

The Mars 2020 mission objectives would benefit significantly from higher precision landing, a priori hazard avoidance, faster mobility, and increased autonomy. The Mars 2020 mission could also potentially benefit from increased mass, payload energy, and volume, though the resources expected from the MSL heritage may suffice in those areas. Since the 2020 opportunity has a more favorable Mars atmosphere density at arrival, the MSL-heritage EDL system can access the desired landing site altitudes.

Furthermore, future Mars surface missions could benefit from any or all of these improved capabilities. A Mars sample return mission would need to land a large ascent rocket and a fetch rover close enough to a cached sample to retrieve it within the lifetimes of those elements. All of the improved capabilities listed above have the potential to reduce the development and mission risk of the retrieval and ascent mission by landing closer to the cache, which may be in a more hazardous or higher-altitude location than where the caching mission landed, being able to get to the cache faster, and being able to land a system with a higher mass than previously demonstrated.

Major Finding D-6: Mars 2020 offers important opportunities for potentially valuable technology development that will reduce risk and improve landing site access and science productivity.

3.6.2 Technology and Measurement Options and Priorities

A number of technologies and measurements (Table 3-14) were considered for flight on Mars 2020. They were assessed for their benefits to Mars 2020, their feed-forward benefits to future missions such as MSR retrieval and ascent, the benefit to the advancement of the technology to be demonstrated on Mars 2020, the ability of the system to accommodate the required resources, and the development and mission risks.

3.6.2.1 Range Trigger (high priority)

On past Mars landers, the parachute has been deployed as early as possible, using an estimation of velocity as the trigger. If there is sufficient altitude margin, the parachute could be deployed anywhere between a maximum velocity and a minimum altitude. Range trigger makes that choice based on the range to the target. If the vehicle were to otherwise overshoot the target, the parachute would be deployed earlier. If the vehicle were to otherwise fall short of the target, the parachute would be deployed later.

This strategy reduces the miss distance to the target, considerably reducing the downtrack dimension of the landing ellipse. The MSL major axis of 25 km could be reduced to 13 to 18 km with Range Trigger. This would open up a much larger set of candidate landing sites, and would potentially permit the placement of the landing ellipse closer to the desired science targets. Examples of high-value sites requiring smaller ellipses enabled by Range Trigger can be found in Melas Chasma.

Range trigger would reduce the risk of a future MSR retrieval by enabling landing closer to the cache. Range trigger would be expected to be a low-cost, low-risk implementation, and its operation would be constrained to not increase the risk of EDL. This technology is proposed for Mars 2020 with high priority, including its use in a mission-critical application.

Table 3-14. Candidate STMD Technologies and Measurements

Technology / Measurement	Benefits	2020 mission critical vs. Feed Forward	Accommodation difficulty / Development risk	Priority
Range Trigger	Smaller landing ellipse	2020 mission critical	Very Low	High
Terrain-Relative Navigation	Avoid landing hazards visible from orbit	2020 mission critical	Medium	High
MEDLI	Reduce thermal protection performance uncertainties	Feed forward performance data	Low	High
MEDLI+Up	Reduce parachute performance uncertainties	Feed forward performance data	Medium	High
Terminal Hazard Avoidance	Avoid landing hazards not visible from orbit	Feed forward demonstration and characterization - consider 2020 mission critical	High	Medium to High
Direct-to-Earth Optical Communication	Increase data volume, data energy efficiency, relieve dependence on orbital assets	Feed forward demonstration and characterization	Very High	Medium
Proximity Optical Communication	Increase data volume, data energy efficiency, add requirement of optical comm orbital assets	Feed forward demonstration and characterization	High	Low
Collocation of Attitude Determination and Inertial Measurement	Smaller landing ellipse	2020 Mission Critical	Medium	Low
Deep Space Atomic Clock	Enable reduced cost and autonomous navigation of future spacecraft	Feed forward demonstration and characterization	Low (if on cruise stage)	Low
Increased Divert Capability for TRN	Avoid larger hazards visible from orbit, land closer to science target	2020 Mission Critical	Medium	Low
Ringsail Parachute	Increased landed mass and/or altitude	2020 Mission Critical	Low (assuming successful LDSD development)	Low
Fast Propulsion System Priming	Increased landed altitude	2020 Mission Critical	Medium	Low
Improved Battery Chemistry	Increased energy capacity and/or increased payload volume	2020 Mission Critical	Low	Low
Distributed Motor Controllers	Increased payload volume and improved operability	2020 Mission Critical	High	Low
Low-temperature actuators	Increased latitude capability	2020 Mission Critical	High	Low
Low-temperature batteries	Increased latitude capability	2020 Mission Critical	Medium	Low
Increased image processing capability for autonomous driving	Double the drive distance per sol	2020 Mission Enhancing	Medium (assuming application of successful TRN development)	Low
Demonstrate future high-performance general-purpose space computers	Enable high-performance multi-core space computers for future missions	Feed forward demonstration and characterization	Medium (assuming hosting on TRN compute element)	Low

3.6.2.2 Terrain-Relative Navigation (high priority)

On past Mars landers, the location of the target relative to the vehicle has been estimated using inertial propagation from a time before the vehicle enters the atmosphere of Mars. The accumulated error from that propagation is on the order of one to two kilometers. Terrain-relative navigation (TRN) significantly increases the accuracy of the estimated location by matching visual images of the surface taken by an on-board camera to a stored map of the surface that was constructed using images taken from orbit (See Fig. 3-23). This approach could reduce the error in the estimated location of the vehicle relative to the target to less than 60 meters. Knowledge of the location could be used to avoid hazard areas in the landing site by diverting around them. The MSL heritage already provides a divert capability as part of assuring separation from the backshell and parachute. The direction of that divert could be selected to avoid hazard areas up to 300 meters in diameter.

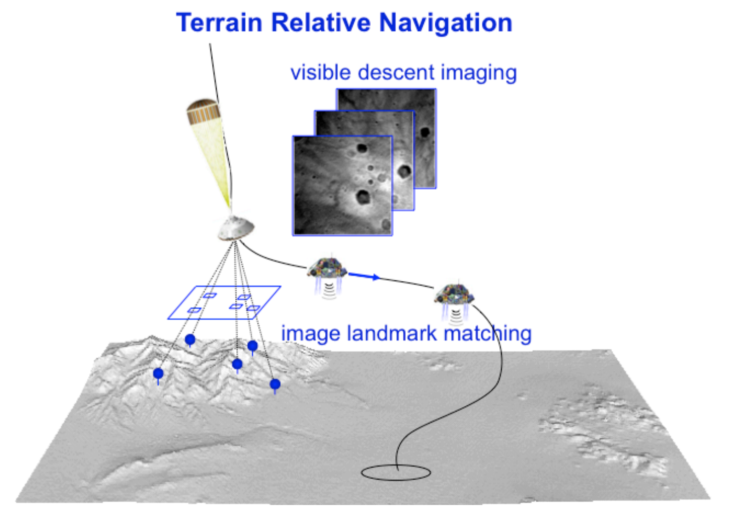


Figure 3-23. Terrain relative navigation would enable access to more high priority science field sites*. This technology improvement to EDL capabilities would enable more precise landing.*

Previous Mars landing sites were required to be free of landing as well as roving hazards to about the 99% level across the entire ellipse. The combination of TRN and a divert capability would open up a much larger set of landing sites that have a higher proportion of hazardous areas, so long as the hazards could be diverted around. There exist high-value sites that without TRN would be too hazardous to select, such as E Margaritifer and NE Syrtis. TRN would potentially reduce the risk of an MSR retrieval, again by enabling a landing closer to the cache, which may be in an area with avoidable landing hazards.

TRN would be a high-risk development. However if the development cannot be completed, then a landing site that does not depend on TRN would be selected. Given a successful development and the selection of a landing site dependent on TRN, the mission risk would be higher for this first time use. Sufficient project resources would need to be allocated to verify and validate the TRN capability in order to minimize this risk.

TRN is proposed for Mars 2020 as a high priority, including its use in a mission-critical application.

TRN is not currently at Technology Readiness Level (TRL) 6, and would require maturation before the Mars 2020 Preliminary Design Review (PDR), currently planned for 2015. The SDT concludes that such an effort should be initiated as soon as possible.

3.6.2.3 MEDLI (high priority)

The Mars Entry, Descent, and Landing Instrumentation (MEDLI) investigation flew successfully on MSL, where it successfully collected data on the forebody heatshield performance and entry environment. It was funded in a partnership between HEOMD, Aeronautics Research Mission Directorate, and SMD, and was later adopted into the STMD program. The returned data would be critical to updating, calibrating, and validating models of the environment and response of the thermal protection system, since there is no way to subject the system to a relevant environment other than in flight at Mars. The MEDLI data has exposed both non-conservative and conservative aspects in the design of the thermal protection system. This should permit a better balance of risk in future heatshield design. Several gaps remain in our understanding of the heating during entry. A reflight of MEDLI is proposed for flight on Mars 2020 with high priority. Lessons learned from the MSL flight can be applied to maximize the data return from Mars 2020; for example in relocating sensors based on the updated knowledge of the flow field. There should also be additional consideration of new sensors to better understand the forebody heating, as well as adding backshell sensors.

3.6.2.4 MEDLI+Up (high priority)

MEDLI focused on the entry phase of EDL with sensors located only on the heatshield. The descent phase also depends on models with significant uncertainty, in particular models of the supersonic parachute deployment and operation. Those empirical models are based on limited and incomplete data collected on smaller parachutes more than forty years ago in Earth-based experiments, plus what can be deduced from MSL and earlier EDL reconstructions where atmospheric density and parachute drag effects are mixed in the data. "+Up" Instrumentation that could directly observe the deployment and operation of the parachute at Mars using upward-looking cameras, combined with direct measurements of the parachute drag would dramatically reduce the model uncertainties, as well as expose any incipient failure modes or other risks in the operation of a supersonic parachute at Mars.

The +Up augmentation of MEDLI is proposed for Mars 2020 with high priority. Though such instrumentation could be implemented with existing technology, the instrumentation concept is at a low level of maturity. Therefore a development effort should be initiated as soon as possible in order to be viable by the time of the Mars 2020 PDR.

Finding D-7: The high-priority technology payloads, based on benefit and risk are: Range Trigger, Terrain-Relative Navigation, and MEDLI/MEDLI+Up.

3.6.2.5 Terminal Hazard Avoidance (medium-high priority)

Some landing hazards are too small to see with current or anticipated orbital assets. Such hazards could only be avoided with a system that could detect and correctly identify those hazards autonomously and in real-time during terminal descent (Fig. 3-24). Then terminal descent guidance could then be instructed to avoid those hazards. The combination of a hazard sensor and guided avoidance is Terminal Hazard Avoidance (THA). THA requires a new LIDAR sensor development for the 3D mapping of hazards in real time. A THA system could share compute resources with a TRN system.

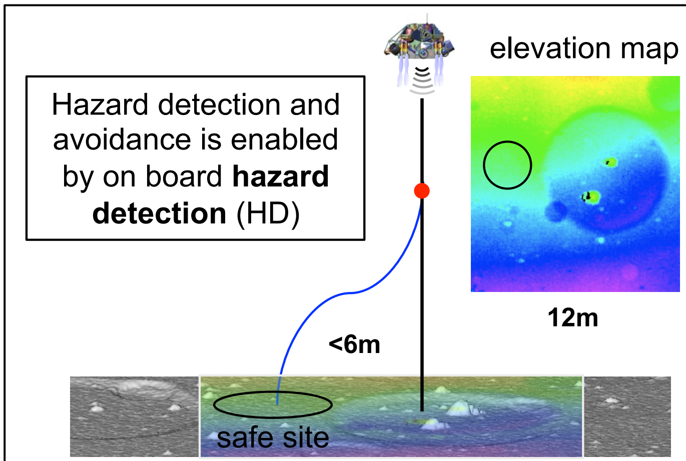


Figure 3-24. Terminal hazard avoidance would reduce the landing ellipse size, allowing a spacecraft to land in a larger variety of field sites. *During descent, on-board LIDAR sensor and computer processor systems locate small-scale hazards undetected/undetectable from orbit, and controls descent thrusters to move the landing site away from the hazard.*

Jezero Crater is an example of a high value site that would be deemed safe only if THA could be relied upon for mission success. THA would enable a set of high-value landing sites beyond what would be enabled by TRN, albeit a smaller set. There may be sites with similar scientific benefits that do not require THA, but that would not be known until the landing site selection process is well underway.

If relied upon for mission success, THA would be a high-risk and high-cost development. Due to the smaller increase to enabled science and higher development risk as compared to TRN, THA is proposed as a medium priority for Mars 2020. The development cost and risk could be reduced by not relying on THA for mission success in 2020. In that case, the data collected by the THA system on terminal descent in the actual Mars environment would be returned after landing and used to advance the readiness of the technology and enable its application on a subsequent mission at much-reduced development risk. In this case, the data from the THA sensor would not be used by the guidance system on 2020. To enable the widest possible range of landing sites and the best science return for future missions, the non-mission-critical flight of a THA sensor on 2020 should be given serious consideration after the high-priority technology payloads have been accommodated.

3.6.2.6 Direct-to-Earth Optical Communication Terminal (medium priority)

Mars surface missions rely on UHF relay links for the majority of the returned data volume, measured in hundreds of megabits per sol. These links require at least one orbital asset to support the relay. Due to the uncertainty of the survival of these assets by the time any given surface mission arrives, a high-gain direct-to-Earth (DTE) X-band radio is often implemented on these surface missions as well, as a back-up means of communication, albeit at much lower data volume and greater power consumption. The Mars Exploration Program maintains multiple orbital assets for surface communication relay, requiring the launch of new spacecraft to replace old ones. The spacing of surface missions in time is not much shorter than the lifetime of the orbital assets, resulting in the possibility of having to expend significant resources to replace an aging or defunct relay asset when an orbital mission might not have otherwise been required for scientific reasons.

Optical communication, using finely pointed lasers to carry high-rate data directly to Earth, could provide greater energy efficiency and greater data volume than a relay, without the need for an orbital asset, and without the need for a high-gain DTE X-band system. (A low-gain X-band DTE on the surface mission may still be desired for emergency communication in the event the optical communication system is temporarily unable to point to Earth due to spacecraft fault conditions.) At comparable power levels, a DTE optical system to a 5-meter ground telescope could provide almost double the data volume of a UHF relay over a martian year, or to a 12-meter telescope, ten times the data volume.

That comparison assumes the same amount of contact time per sol as the UHF relay, on the order of half an hour. UHF relays are inherently limited due to the short visibility of any given relay orbiter, usually two passes a day for about 15 minutes each pass. A DTE optical communication link on the other hand could operate whenever Earth is sufficiently above the horizon, which is for roughly half of every day. So if desired, even greater data volumes are achievable with DTE optical communication, if that is a scientifically beneficial way to expend that energy. Currently far more camera images can be acquired than can be returned. In fact many images that are taken are never returned through the current UHF links, where the ones that are returned are prioritized on the basis of reduced resolution thumbnail versions of all of the images.

DTE optical communication offers the potential to not only eliminate reliance on a costly orbital infrastructure, but also to increase the possible data return from surface assets by one to two orders of magnitude.

Such a deep-space optical terminal has never been developed to a level of flight qualification, nor demonstrated in deep space. The technology is not at a sufficient level of readiness at the system level to be relied upon for mission success in 2020. Therefore if such a system were to be flown on Mars 2020, it would need to coexist with a UHF relay and a DTE X-band system. The demonstration of such a system on 2020 would enable later missions to rely on optical communication for mission success. However, the physical volume required for all of those systems would be problematic at best on an MSL-heritage rover for 2020, taking into account the volume needs of other expected payload elements. The development cost and risk would be high, though mission success would not depend on it. While the mission resources required and development risk are both high, the value of such a demonstration to future Mars surface missions, as well as the value to future orbital missions, would be very high. As a result, such a demonstration is proposed for Mars 2020 at medium priority.

3.6.2.7 Proximity Optical Communication Terminal (low priority)

An alternative optical communication demonstration is possible that would require significantly less physical volume. A small proximity optical communication terminal only able to communicate with an optical communication asset orbiting Mars could be demonstrated on Mars 2020. Such a demonstration would enable a different architecture that still would depend on orbiting assets just as the current UHF relay architecture does. However such a system could provide even higher data volumes if required, two to three orders of magnitude greater than the current UHF systems at comparable energy usage. However such a demonstration would require that a new orbiter with a companion proximity optical communication terminal arrive at Mars within the lifetime of the Mars 2020 mission. Such a demonstration would be endorsed only if there was an associated plan for such an orbiter. A proximity link demonstration would require some, but not all of the risks of a DTE optical terminal. As a result of the lower benefit, i.e. continued reliance on an orbiting infrastructure and a limited retirement of the risks of a DTE terminal, consideration of a proximity optical communication should be consider at low priority, and then only if a companion orbiter mission is planned.

3.6.2.8 Other Entry, Descent, and Landing Enhancements (low priority)
Landing precision could be further improved beyond Range Trigger. The initial attitude determination error before entry into the atmosphere is a contributor to the landing ellipse size. Physical collocation of the star scanner that determines the attitude, and the inertial measurement unit that propagates the attitude, would remove much of the mechanical alignment uncertainty that exists in the heritage system.

A deep-space atomic clock would permit later and improved atmospheric entry location knowledge through the use of a one-way navigation data type. The knowledge is used during atmospheric guidance. This is a smaller, but still noticeable contributor to the landing footprint.

With more propellant or more optimal use of propellant, a larger divert during terminal descent would be possible. This could be used to remove some of the error introduced during descent on the parachute, with the aid of the location knowledge from TRN. An increased allocation of propellant as well as optimal divert software could increase this divert capability.

In addition to precision, there are technologies that can improve the altitude and mass capabilities of the EDL system. A ringsail parachute larger than the MSL disk-gap-band parachute and operable at higher Mach could increase the landed mass capability of the system, the altitude capability, or some combination. The Low Density Supersonic Decelerator project plans to develop such a parachute for Mars applications and bring it to the readiness required by a Mars 2020 development schedule.

The time required to prime the terminal descent propulsion system could be reduced by several seconds, which could increase the altitude capability by several hundred meters.

Due to the smaller benefits of collocation and deep space atomic clock, and the system accommodation impacts of increased divert, the ringsail parachute, and fast priming, all of the technologies in this subsection are proposed for consideration at low priority. The deep space atomic clock technology would increase its readiness level for other missions by flying and being used on 2020. This would feed-forward to overall SMD mission benefits in reduced DSN usage and operational costs through the application of autonomous navigation. The other technologies in this subsection would already be at the readiness required for use in a mission, assuming in the case of the ringsail that that development would be successful, and so they should be considered for Mars 2020 only with regard to the benefits to the Mars 2020 mission objectives. Though the mass benefit of the ringsail parachute would not be needed at this time, the definition of the Mars 2020 systems are still at an early stage in formulation. It would be prudent to keep the option open to accommodate the ringsail if its development is successful and if it is needed by Mars 2020.

3.6.2.9 Improved Surface Operational Productivity (low priority)
As noted in finding 7-3 of this report, the productivity of the system in the conduct of the science activities and the collection of a returnable cache of samples is a high priority. There are technologies that could be applied to improve productivity and increase latitude access. An assessment of the heritage

system indicates that it could meet the basic operational needs and the latitudes of candidate landing sites. (See sections 7 and 8.) The requirements of future Mars rover missions are not likely to be significantly different. As a result, all of the technologies in this subsection are proposed for consideration with low priority. However as the project proceeds through formulation, much more detailed assessments of the surface operations may give a different answer. If so, the priorities of these technologies should be reconsidered.

New battery chemistries have been developed that provide double the energy density per unit volume. This could permit more volume for other payload elements, more energy storage for operations, or some combination. What remains for the technology is the packaging of the cells into flight batteries. This should be a relatively low-risk development.

Distributed motor controllers, where the control electronics are closer to the actuators, could provide more payload volume and greater operability of the motors. Such a development was begun for MSL, but then abandoned. Based on that experience, the development risk is considered to be high.

Low-temperature actuators would avoid having either to wait for the actuators to warm up, or to use energy from the batteries to heat them, before using them for driving or other operations. This could permit more driving in a sol or less energy required for driving at high latitudes. Such a development was also initiated on MSL and then abandoned. Considering that, and the development of the existing technology actuators for MSL, this is considered a high-risk development. However the long-term benefits for Mars surface missions could be significant.

Low-temperature batteries, operable down to –40°C, are considered achievable, with some development and packaging work. This could increase the latitude access of the system to colder climes, and potentially improve the energy efficiency when electrical heating of current technology batteries would otherwise be required.

Increased image processing capability for autonomous driving could double the drive distance per sol by effectively eliminating the time spent thinking between movements. If a TRN system would be flown on Mars 2020, then the compute element of that system could be used for faster traverses with a firmware update after landing. This would require that the TRN compute element be on the rover and operable during the surface mission, that its firmware be updatable, and that there be a high-speed data link between the TRN compute element and the rover compute element to permit the rapid transfer of camera images. If there is a TRN system on Mars 2020, the SDT feels strongly that these conditions should be met in order to permit the possibility of using the TRN compute element for fast traverses in the surface mission. Even if the development of fast traverse software and firmware would not be part of the pre-launch development, it should not be precluded for post-launch, surface, or extended mission development.

The TRN compute element would also be an opportunity to serve as a host for the demonstration and characterization of future higher-performance computers for space missions. A multi-core computer card could be used experimentally during the surface mission. It would be off during the mission-critical EDL application of TRN. The demonstration of significantly improved multi-core computational capability would be a feed-forward benefit for many SMD missions.

4 Traceability Matrix

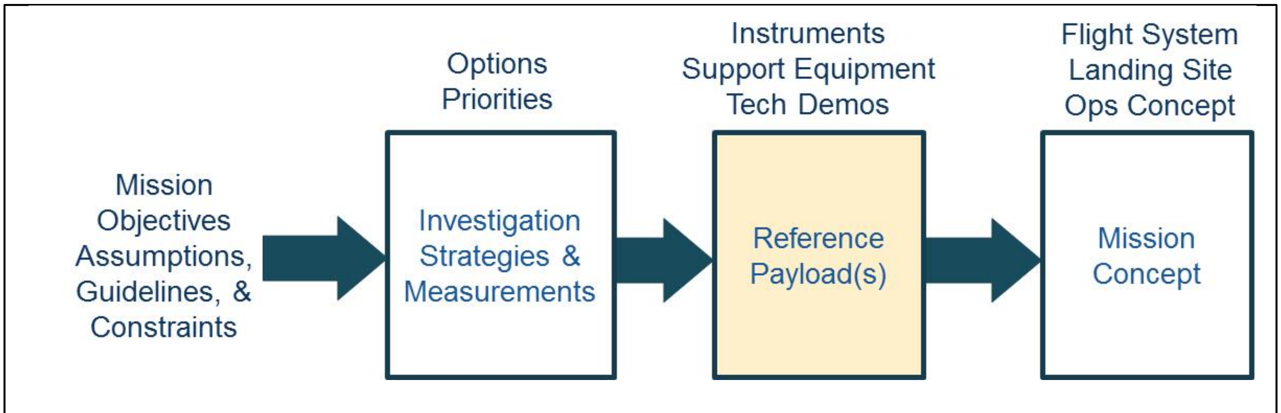
Science traceability matrices were constructed for each of the Mission Objectives A, B, and C as described in the following text. Based on results of previous science sub-teams, key science goals were identified within each Mission Objective. As an illustrative example from Objective B, to assess the biosignature preservation potential within the selected geological environment, a science goal would be to understand the potential for biosignature preservation (Table 3-6-first column-first row). Within that goal, there are smaller-scale objectives. One of those would be to determine processes and conditions in the paleoenvironment for the early formation of potential biosignatures (Table 3-6-second column-first row). To address this smaller-scale science objective, multiple measurement objectives are required. One of these measurement objectives would be to understand distribution of grain sizes, shapes and compositions (Table 3-6- third column-fourth row). This measurement objective could be met by four types of measurements, fine-scale imaging, fine-scale mineralogy, elemental chemistry in the arm's work volume and organic chemistry detection in the arm's work arm (Table 3-6-blue boxes in the sixth to ninth columns-fourth row). Meeting this objective places requirements on the spatial resolution capabilities of all four measurement types (as noted in the blue boxes and described in detail in Section 3.2.2.3). For each mission objective, each subsidiary science goal was similarly expanded into smaller-scale science objectives, then measurement objectives, then types of requirements placed on the *in situ* measurements. This was done both for science threshold investigations as well as for possible additional baseline investigations. This traceability from top-level goals to performance requirements for each investigation is shown in matrix form separately for Mission Objectives A, B, and C in Tables 3-1, 3-7, and 3-10.

For readability of the matrices, the exact specifications for each type of requirement that is placed on the investigation - its sensitivity, spatial resolution, footprint, etc. - was not listed repeatedly. Rather, the most demanding specification for each type of requirement on each *in situ* investigation was collected in one place, in Table 4-1.

Table 4-1. *Science Traceability Matrix for the Proposed Mars 2020 rover.*

Driving Requirements for Threshold and Baseline Investigations and Recommended Performances													
	Observation spatial footprint			Spatial resolution or sampling (NOTE 1)			Data quality			Detection capabilities			Other requirements
	Requirement	Suggested Performance		Requirement	Suggested Performance		Requirement	Suggested Performance		Requirement	Suggested Performance		
		Baseline	Threshold		Baseline	Threshold		Baseline	Threshold		Baseline	Threshold	
Threshold science support hardware													
Surface preparation tool	≥2.5 cm (NOTE 2)			N/A			N/A			N/A			REQUIREMENT: Remove dust and coatings from rock surfaces, and allow measurement tools to distinguish the two. SUGGESTED PERFORMANCE: Remove dust only, and also remove a firmly adhering coating or rind
Threshold science investigations													
Context imaging	Survey the scene for geologic structures.	Panoramic capability, elevation +20° to -75°	Same as baseline	Image sand-sized particles at base of rover.	Resolve 1 mm feature at 2 m, 40 cm feature at 1 km	Same as baseline	Provide adequate dynamic range to detect variations in shape and color.	SNR >200, for reflectance 0.3 at 30° phase angle	SNR >100, for reflectance 0.3 at 30° phase angle	Measure shape of geologic features accurately enough to support interpretation of geologic processes.	Zoom capability added to threshold requirements	Range resolution 1 mm at 2 m, 2 cm at 10 m distance using stereo or other methods	REQUIREMENT: Discriminate "fresh" from oxidized materials. SUGGESTED PERFORMANCE: Multiple bandpasses at 0.4-1.0 µm, justified by the proposer REQUIREMENT: Support rapid-turnaround generation of science analysis products; SUGGESTED PERFORMANCE: Compression and data management capabilities to support downlink of a 1-color panorama in ≤2 sols
Context mineralogy	Collect / downlink contiguous measurements of a scientifically interesting exposure.	Contiguously survey ≥30° x 30° solid angle within a measurement cycle	Contiguously survey ≥10° x 20° solid angle within a measurement cycle	Detect a compositionally distinct nearby pebble or cobble.	Sampling scale ≤1 cm at 10 m distance	Sampling scale ≤10 cm at 10 m distance	Detect a compositional difference covering a single measurement cell.	Detect a 0.5% mineral signature (e.g., absorption or emission) in 1 cell of a measurement matrix.	Detect a 1% mineral signature (e.g., absorption or emission) in 1 cell of a measurement matrix.	Identify major mineral phases indicative of igneous, sedimentary and alteration processes.	Add halides to threshold; distinguish among phases within classes	Discriminate minerals within classes: primary rock-forming silicates, OH- and H2O-bearing secondary silicates, silica, sulfates, carbonates, oxides	REQUIREMENT: Function throughout the rover's immediate operational environment. SUGGESTED PERFORMANCE: Assess composition of material at distances to ≥10 m (to ≥20 m desired)
Fine-scale imaging of arm work volume	Determine morphology of microscopic scale features over the area of a petrographic thin	≥2x2 cm in one measurement set	Same as baseline	Distinguish grains, cement, and potential microbial laminae in a sedimentary rock.	Resolve grains larger than medium silt, diameter ≥62 µm	Same as baseline	(Adequacy to be justified by proposer)			Acquire measurements without levying requirements on robotic arm other than coarse sensor	(If using an optical system) autonomously collect data for in-focus measurements	Same as baseline	REQUIREMENT: Distinguish coarse color variations between grains. SUGGESTED PERFORMANCE: Capability to acquire ≥3 color images; specific bands to be justified by proposer REQUIREMENT: Characterize rock coatings as well as prepared surfaces. SUGGESTED PERFORMANCE: Perform measurements on abraded, brushed, or natural rock surfaces
Fine-scale mineralogy of arm work volume	(Adequacy to be justified by proposer)			Determine compositions of microscale rock components such as veins, matrix, cements, grains and laminae.	Contiiguous samples at scales of ≤0.1 mm	Contiiguous samples at scales of ≤0.5 mm	(Adequacy to be justified by proposer)			Detect major mineral phases indicative of igneous and alteration processes.	Add halides to threshold; distinguish among phases within classes	Discriminate minerals within classes: primary rock-forming silicates, OH- and H2O-bearing secondary silicates,	REQUIREMENT: Co-locate close-up measurements. SUGGESTED PERFORMANCE: Measure same surfaces as fine-scale imaging and elemental chemistry investigations. Provide data for co-location to ≤ 0.5 mm in fine-scale images. REQUIREMENT: Characterize prepared surfaces; brushed or natural surfacces desired. SUGGESTED PERFORMANCE: Tolerate roughness ±0.5 mm of prepared target using operational approaches
Fine-scale elemental chemistry of arm work volume	(Adequacy to be justified by proposer)			Determine elemental composition of rock components	Contiiguous samples at scales of ≤0.1 mm	Sampling scale of measurement ≤2 cm	Detect differences in relative abundances of major elements between measured materials.	Detect Si, Al, Fe, Mg, Ca, Na to ±10% precision integrated over 2x2 cm area, if present at ≥1000 ppm	Adequacy to be justified by proposer	Detect minor elements whose abundances are indicative of sedimentary, igneous and alteration processes.	Detect K, P, S, Cl, Ti, Cr, Mn over 2x2 cm area, if present at ≥100 ppm	Adequacy to be justified by proposer	REQUIREMENT: Co-locate close-up measurements. SUGGESTED SUGGESTED PERFORMANCE: Measure same surfaces as fine-scale imaging and mineralogy investigations. Provide data for co-location to ≤ 0.5 mm in fine-scale images. REQUIREMENT: Characterize rock coatings or prepared surfaces. SUGGESTED PERFORMANCE: Perform measurements on abraded, brushed, or natural surfaces. Tolerate roughness ±0.5 mm using operational approaches
Organic detection	(Adequacy to be justified by proposer)			Detect organics over scales no larger than a petrographic thin section.	Contiiguous samples at scales of ≤0.1 mm	Sampling scale of measurement ≤2 cm	Distinguish families of organic compounds if present.	Detect aromatics or aliphatics at <1E-5 fraction bulk OR at <1E-2 with <100 µm sampling scale	Same as baseline	(Adequacy to be justified by proposer)			REQUIREMENT: Perform measurement non-destructively. SUGGESTED PERFORMANCE: Alllow replication of the measurement. REQUIREMENT: Characterize prepared surfaces; brushed or natural surfacces desired. SUGGESTED PERFORMANCE: Tolerate roughness ±0.5 mm of prepared target using operational approaches
Additional possible baseline science investigations													
Second, complementary organic detection measurement	(Adequacy to be justified by proposer)			Detect grain-scale variations in organics.	Contiiguous samples at scales of ≤0.1 mm	Same as baseline	Distinguish families of organic compounds if present at the grain scale.	Detect aromatics or aliphatics at <1E-2 fraction in a single pixel of the measurement	Adequacy to be justified by proposer	(Adequacy to be justified by proposer)			REQUIREMENT: Perform measurement non-destructively. SUGGESTED PERFORMANCE: Allow replication of the measurement. REQUIREMENT: Characterize prepared surfaces; brushed or natural surfacces desired. SUGGESTED PERFORMANCE: Tolerate roughness ±0.5 mm of prepared target using operational approaches
Subsurface compositional sensing	Detect variations in subsurface composition over scales comparable to local geologic variations.	Detect variations over length scale of rover	Adequacy to be justified by proposer	Detect compositions obscured by dust or regolith removable by rover operations.	Detect compositions obscured by 5 cm of global average dust.	Adequacy to be justified by proposer	(Adequacy to be justifited by proposer)			Detect subsurface enhancements of compostions indicative of aqueous alteration.	Detect silica, sulfate, carbonate, or water with an abundance twice or more that of the dust layer	Adequacy to be justified by proposer	REQUIREMENT: Measure sub-surface composition with minimal impact on rover operation. SUGGESTED PERFORMANCE: Perform measurement without active trenching
Subsurface structural sensing	Detect variations in subsurface structure over scales comparable to local geologic units.	Capability for measurements to 10 m depth	Adequacy to be justified by proposer	Detect variations in structure at scale of sedimentary beds or large clasts of ejecta.	30 cm along-track and vertical resolution	Adequacy to be justified by proposer	(Adequacy to be justifited by proposer)			(Adequacy to be justifited by proposer)			N/A
NOTE 1: For compositional measurements the scale of an individual measurement cell is indicated. For imaging measurements the scale of the feature to be resolved is indicated, whereby a resolution requirement is show to be achieved using modulation transfer function or comparable analysis.													
NOTE 2: The size of the prepared surface should be larger than the largest fine-scale field-of-view plus positioning uncertainties for the measurement.													

COLOR LEGEND
Science threshold
Science baseline
Science support threshold



Current location in the "Roadmap"

<u>*The Mars 2020 rover would…*</u>

…meet the science objectives with a set of powerful yet affordable instruments.

5 Payload Instrument Options

5.1 Introduction

This section concerns the array of instruments that could be carried on the rover. The instruments can be classed into two broad categories: those whose primary goal would be to address the science objectives of geology, habitability and caching, and those whose primary goal would be to help prepare the way for eventual human exploration. The total cost of the instruments in the first category is limited to approximately \$100 M (see Appendix 1) and instruments in the second category are expected to be limited to approximately \$25M (a preliminary planning input from HEOMD to this study). They must be accommodated on a Curiosity-class rover and are preferred to be at TRL-5 or higher.

5.2 Potential Science Instruments

5.2.1 Background

We saw above in sections 3.2.2.2, 3.3.2.2 and 3.4.2 that the measurements needed to geologically explore a landing site, to assess its past habitability and to select samples for caching are similar. For each science objective, the threshold measurements, that would be the irreducible set of measurements required to minimally accomplish the science objectives, are context imaging and mineralogy, and fine scale imaging, fine scale mineralogy and fine scale elemental chemistry of the arm work volume. A brief description of the required capabilities of each of the five threshold contextual and close-up investigations is given in Section 3.2.2.2. Objective B, assessment of past habitability, requires detection of organic carbon in addition to the five common threshold measurements. The large overlap in the threshold measurements for the three science objectives leads to the following finding.

Major Finding 5-1: The measurements that would be required to meet the geology and habitability, biosignatures, and caching objectives are similar. Thus, these three objectives are compatible and well-suited to be assigned to the same mission

5.2.2 Proposed "strawman" threshold payload options

Several high priority measurements beyond the irreducible threshold would significantly augment the value and reduce the science risk of the mission. These have been termed baseline measurements and include detection of organic carbon and subsurface sensing for objective A, characterization of organics for objective B and detection of organics for Objective C. We have further identified enhancements, which are measurements beyond the baseline and threshold that would significantly increase the interpretability of the threshold and baseline measurements. Possible enhancements include molecular analysis of organics and paleomagnetic measurements. The various proposed measurements are summarized in Table 5-1. Most of the measurements listed in Table 5-1 could be made with more than one instrument as shown in Table 5-2.

A major issue with respect to the payload is whether there are sufficient resources for laboratory-like instruments, such as the SAM instrument on Curiosity, that require sample acquisition and processing capabilities, and space and other resources within the body of the rover. The issue would be of particular importance for performing molecular analysis of organics as part of the search for potential biosignatures. However, inclusion of such instruments would be incompatible with the current guidelines on cost and resources and could occur only if resources well beyond the guidelines given become available. In addition, should an instrument be offered by another agency, the volume and sample delivery issues would still remain to be resolved.

Table 5-1. The same five measurements can meet objectives A, B, and C. *Measurements needed to evaluate the geologic environment of the rover, to aid in the search for biosignatures and to support selection of samples.*

<table>
<tr><th>Objective A
Geology</th><th>Objective B
Biosignatures</th><th>Objective C
Caching</th><th>Objective D
HEO/Tech</th></tr>
<tr><td colspan="3">THRESHOLD
Instruments addressing all 6 threshold measurements</td><td rowspan="2">OPTIONS</td></tr>
<tr><td>Measurements/Capabilities</td><td>Measurements/Capabilities</td><td>Measures/Capabilities</td></tr>
<tr><td>•Context Imaging
•Fine-Scale Imaging
•Context Mineralogy
•Fine-Scale Elem Chem
•Fine-scale Mineralogy</td><td>•Context Imaging
•Fine-Scale Imaging
•Context Mineralogy
•Fine-Scale Elem Chem
•Fine-scale Mineralogy
•Reduced/Organic C detection</td><td>•Context Imaging
•Fine-Scale Imaging
•Context Mineralogy
•Fine-Scale Elem Chem
•Fine-scale Mineralogy</td><td rowspan="6">• ISRU Demo
• EDL Data
• EDL Precision & Site Access
• Surface Weather Monitoring
• Biohazards to Astronauts</td></tr>
<tr><td colspan="3">BASELINE OPTIONS
Enhanced-capability instrument(s) in THRESHOLD category OR add one of the following:</td></tr>
<tr><td>•Subsurface Sensing
•Organic C detection</td><td>•2nd method of Organic C Detection</td><td>•Organic C Detection</td></tr>
<tr><td colspan="3">ENHANCED OPTIONS
Enhanced-capability instrument(s) in THRESHOLD category AND an additional BASELINE or ENHANCED instrument</td></tr>
<tr><td></td><td>•Molecular Analysis</td><td></td></tr>
</table>

The instruments listed in Table 5-2 should not be taken as an endorsement of any specific instruments. The table is included to illustrate four points. First, some instruments can make dual measurements. VISIR multispectral imaging could, for example, determine both context imaging and context mineralogy. Flight of an instrument to make dual measurements could lead to cost saving thereby enabling a broader range of measurements to be made. Second, several of the measurements could be made with multiple techniques. Fine scale imaging may, for example, be accomplished by a VISIR microspectrometer, a VISIR multispecral microimager, by X-ray fluorescence or by Raman based techniques. The sensitivity of remote sensing instruments to composition varies according to the measurement technique and the wavelength range observed so that one technique cannot view all relevant wavelengths with optimal sensitivity. Thus there is commonly an advantage to applying multiple techniques to a particular measurement to get a more complete analysis. Third, an instrument whose prime function is one measurement may contribute to the understanding of other measurements. How well the instrument contributes to that second category of measurement depends on the specific instrument characteristics. Fourth, the table illustrates the point that selection of the instruments that are ultimately proposed should be viewed in the context of an array of mutually supportive instruments rather than as making several independent, isolated measurements. This discussion leads to the following findings:

> **Finding 5-2:** A variety of implementation options could satisfy the proposed measurements to meet mission objectives {there are other instruments that could be proposed that are not listed in Table 5-2

Table 5-2. Some kinds of measurement functionalities can be combined into single instruments, while others may make complementary measurements. *Threshold measurements and implementation options*

	Context imaging	Context mineralogy	Fine-scale imaging	Fine-scale Mineralogy	Elemental composition	Reduced C, Organic C detection
Visible multispectral imaging	Major contribution	Some contribution				
VISIR* multispectral imaging	Major contribution	Major contribution				
VISIR imaging spectroscopy	Some contribution	Major contribution				Some contribution
VISIR or TIR point spectroscopy		Major contribution				Some contribution
Raman-Based Techniques		Some contribution	Some contribution	Major contribution		Major contribution
VISIR multispectral micro-imaging			Major contribution	Major contribution		
VISIR micro-spectroscopy			Some contribution	Major contribution		Some contribution
X-ray fluorescence			Some contribution		Major contribution	
Laser induced Breakdown Spec.		Some contribution			Major contribution	

*VISIR indicates ~0.4 to ~3 microns

Major contribution | Some contribution

> **Finding 5-3:** There are several instruments with dual functionality that appear to provide the opportunity for cost and accommodation savings (Appendix 4). These opportunities should be carefully considered as the instrument competition is evaluated.

> **Finding 5-4:** For some of the threshold capabilities, there is value to complementary measurements using different methods.

As noted, there are several instrument options for making the threshold measurements. Thus, there are multiple ways to build the threshold and baseline payloads. The AO-driven instrument competition should unveil a significant range of possible approaches and the relations between instrument performance and cost. In the selection process, it may not be possible to select the highest performing instrument in each measurement category and stay within the mission's resource cap. Thus, in order to select the optimum payload consistent with the resources available, the instrument selection process will need to compare instrument cost and value between instrument categories in addition to comparing capability, performance and cost in the same category.

> **Finding 5-5:** For each measurement functionality, there are multiple instruments options that represent a range of cost, overall performance and ways of optimizing performance.

5.2.2.1 Possible Science Payload Options

Two strawman payloads were assembled to determine if the six threshold measurements could be made within the cost limit and other constraints such as mass, volume and power. The data used to assemble the payloads are listed in the Appendix, as is the method used to estimate costs. To within cost estimation uncertainty, the two threshold strawman examples shown in Table 5-3 fit within the charter-specified cost constraint of $100M. In addition, preliminary accommodation assessment (see Section 9 of this report) shows that the proposed rover should be able to fit all of the threshold elements of Table 5-3, and most (and potentially all) of the baseline elements. These two examples take different approaches to make each of the six threshold measurements except for context imaging. Other combinations of the known instruments are possible and additional combinations should be possible if, as is likely, instruments in addition to those in the appendix are proposed.

Table 5-3. At least two sets of instruments can meet the science objectives within the proposed cost cap. *Two versions are shown to illustrate that the payload can be put together in more than one way, and for each version baseline and threshold variants are shown. The instrument cost data are binned by High, Medium, Low.*

Functionalities Required	Blue Straw Payload	$M	Orange Straw Payload	$M
Context imaging	**Mastcam-like**	M	**Mastcam-like**	M
Context Mineralogy	**UCIS-like**	M	**mTES-like**	M
Elemental Chemistry	**APXS-like**	L	**µXRF-like**	L
Fine-scale imaging	**MAHLI-like**	M	**MMI-like**	M
Fine-scale mineralogy	**Green Raman-like**	H		
Organic Detection			**Deep UV-like**	H
Science support equipment	Includes cache, sampling system, surface prep tool			
Technology payload elements	Includes range trigger[2]			
Threshold Total (SMD funded)[1]		**~90**		**~90**
Additional Instrument Options	**GPR**	M	**GPR**	M
HEO contributed payload	**ISRU**		**ISRU**	
Technology payload elements	Includes TRN[2]			
Baseline Total (SMD funded)[1]		**~105**		**~105**

[1]*Cost totals are instruments only; do not include science support equipment or non-science contributions.*
[2]*Further discussion of technology payload elements in Section 8*

In assembling the two strawman payloads in Table 5-3, some consideration was given to possible multiple functionalities such as those shown in Table 5-2. Table 5-3 demonstrates that there is more than one solution that exists within the given cost constraints, and in addition that there is more than one strategy to put together an instrument set that would produce all of the required measurements. In evaluating the responses to the AO, numerous trade-offs will need to be evaluated. First, multiple instruments with different costs and performances in each of the threshold measurement categories may be proposed, and it would be possible to select either higher- or lower-performing instruments in each category, consistent with an overall cost constraint. Second, some proposed instruments may be able to make measurements in two or more categories—this offers potentially valuable efficiency (e.g. in mass and volume). This SDT does not know the actual available instrument budget (we are working to a charter-specified figure of $100M, but the actual figure may be higher or lower than this, depending on several factors), and the SDT cannot see the arguments used by the proposers to justify their instruments. Thus, the SDT is not in a position to make such trades. In particular, we cannot evaluate whether any incremental instrument money would best be invested in higher performing instruments in the six threshold measurement categories, or into the capability to make a seventh measurement (see Fig.

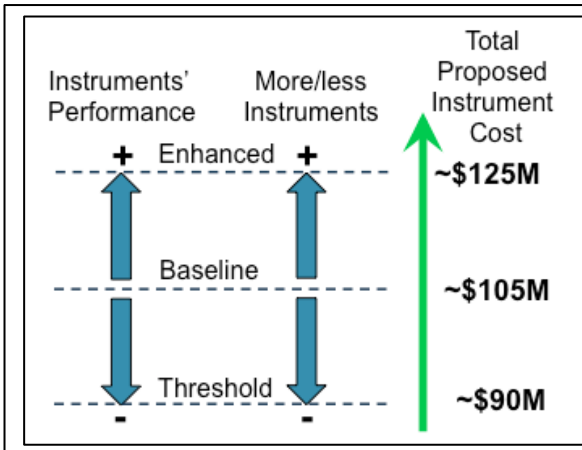


Figure 5-1. Illustration of two key trade-offs associated with selecting the instruments for the proposed Mars 2020 rover. *Navigating these trade-offs would be highly dependent on overall instrument budget. Trade and cost scaling should be part of evaluating the response to the AO, not as part of this SDT.*

5.1). However, in view of these possibilities the AO should call for proposals in all three categories, threshold, baseline and enhancements, in the expectation that the payload will not be narrowly limited to making only threshold measurements.

Based on the cost data available to the SDT, we conclude that a minimum credible set of instruments (i.e. the threshold) to achieve the objectives of this proposed rover would require a budget of about $90M. For a baseline set of instruments, this figure should be about $105M. The instrument budget required for an enhanced mission is hard to estimate, but if we allow for an additional $20M over the baseline level, that should allow for a reasonable competition for an additional instrument among some very interesting possibilities.

5.2.3 Human Exploration Payload Options

5.2.3.1 Payload Resource Requirements and Cost Estimates

We saw above in Section 3.5 that HEOMD identified three payload elements that are high priority. These are an atmospheric ISRU system, MEDLI+, and a surface weather station. The HIT developed estimates of mass, power, and cost for each payload concept (Table 5-4). This information was used to rule out candidate payloads that could not be accommodated on the rover, or that exceeded the available budget. The mass and power estimates were based on similar instruments that have flown on past missions, or on prototype hardware. HEOMD requested detailed cost estimates from the NASA Centers through the Spring 2013 budget formulation process. Technical details and capabilities of these proposed instruments are included in Appendix 5. As will be shown in Section 9, the rover appears to be able to accommodate any of these candidate payload options. The primary limitation on rover accommodation is payload volume because the HEOMD payload and the science instruments would be carried inside the rover's body for thermal control. The MEDLI+ payload would not impact the rover design because it would be installed on the heat shield.

The full Atmospheric ISRU demonstration, which would include CO_2 capture and O_2 production, was estimated to cost $55M. This exceeded HEOMD's available budget, so it was decided to descope the demonstration to focus only on carbon dioxide (CO_2) capture, which reduced the cost to approximately $22M. CO_2 capture is the most difficult part of the overall process for producing O_2 from the martian atmosphere. The CO_2 capture process may be affected by Mars atmospheric conditions such as diurnal and seasonal variations in pressure and temperature, and by suspended dust particles that could clog filters. The process for producing O_2 from compressed CO_2 can be tested on Earth since it does not depend on Mars atmospheric conditions. The SKG for measuring dust size and morphology could also be addressed by this experiment by adding a particle counter and microscopic imager to the intake of the CO_2 capture system. The ISRU experiment's pressure and temperature sensors could acquire surface weather data needed for developing and validating atmospheric models, which has high scientific priority.

The drive to conduct an ISRU demonstration on Mars is to test out the key steps of ingesting CO_2 from a dusty Mars atmosphere and liquefying the gas in the diurnally and seasonally varying Mars climate. Dust abundance, particle shape, size and density of the actual environment must be characterized to test and improve filter designs. Such information is also needed to improve calculation of atmospheric and surface radiation. In the ISRU process trace amounts of water must be removed as part of the liquefaction process.

A preliminary assessment by the project team at JPL has determined that it may be possible to accommodate a descoped atmospheric ISRU payload on the rover, but it would be constrained in volume Table 5-4). A notional design volume has been defined, and HEOMD is working to formulate a system concept that would fit within this volume.

The top three payloads that address high priority SKGs (the descoped atmospheric ISRU demonstration, MEDLI+, Surface Weather Station) are within the cost $25M cost cap. HEOMD has budgeted $25M from FY14 to FY19 in the Advanced Exploration Systems Program for Mars 2020 payload development and integration.

***Table 5-4**. Spacecraft resource requirements for candidate HEOMD Payloads*

Instrument/Demo	Mass (kg)	Power (W)	Operational Concept
MEDLI+	15.1	10	Operates during EDL
Surface weather station	1.3	19	Sampling (approximately 24 times a day)
Atmospheric ISRU demo - CO2 capture + dust - CO2 capture + O2 production	 10 20	 30-50 100-150	Operate 7 to 8 hrs per sol, and as many sols as possible. Operate CO2 capture and O2 production on separate days to maximize production rate

6 Payload Science Support Capability

6.1 Introduction

This section defines the baseline and threshold values for the payload support equipment required to achieve the scientific objectives defined in Section 3. Many of the baseline values for the payload support equipment have been established by previous Science Advisory and Working Groups (E2E-iSAG, 2011; JSWG, 2012; Pratt et al., 2010; MacPherson et al., 2002; MPPG). The strategy of the Mars 2020 SDT was to adopt previously published baseline values, unless there was a scientific/engineering need to change those baseline values (i.e., "if it ain't broke, don't fix it). The SDT evaluated numerous attributes for the payload support equipment; however, only high value science attributes were addressed in detail by the SDT. The following systems/subsystems and attributes were deemed critical to achieve the high priority science and are discussed in detail by the SDT:

1) Sampling System
   a. Minimum required depth of sampling
   b. Precision to which the degree of filling of each sample tube could be measured or verified in the field
2) Caching System
   a. Number of samples
   b. Quantity of cached samples to be replaceable
   c. Sample encapsulation
3) Sample Integrity Subsystem
   a. Organic contamination of samples
4) Sample Processing/Transfer Subsystem
   a. Core/core hole analyses capability by onboard instruments
5) Surface Preparation System
   a. Surface preparation tool

The Mars 2020 rover would…

…be able to collect and document the most exciting rock and soil core samples it discovers as it carries out its exploration activities and store them in a cache.

There are additional attributes of these systems/subsystems that will not be addressed in detail in this report; however, they are listed with baseline/threshold values in the following sections.

6.2 Sampling system

The sampling system consists of a device (e.g., drill) that obtains a sample from rock or regolith and then transfers that sample to a predetermined location, e.g., cache, observation tray, sample processing. Historical baseline values for the attributes of the sampling system along with the SDT baseline and threshold values are listed in Table 6-1. Sample caching capabilities are described in sections 6.2.3. The attribute requirements for sampling depth and precision to measure the degree of sample obtained during sampling are described in sections 6.2.1 and 6.2.2. Although the attributes of the sampling system listed above were deemed to have a high impact on the 2020 mission science objectives; several additional sampling system attributes were briefly addressed by the SDT. The baseline values established by previous SAGs and WGs for these attributes were adequate to achieve the 2020 mission objectives and are briefly described here.

<u>Capability for number of samples to be acquired for caching or potential caching</u>: The capability to collect about 30-35 samples has been proposed by previous working groups (E2E-iSAG; 2011; JSWG, 2012) based upon the need to survey and/or collect a diversity of samples at the landing site to characterize the geologic setting. The approximate baseline number of samples to be cached was 31 with the capability to replace 25% (i.e., 7 samples) of the previously cached samples that led the capability to collect approximately 38 samples.

The proposed baseline value for the Mars 2020 mission would be the capability to collect 38 samples. This baseline value includes the baseline capability to replace 25 % of previously cached samples OR eliminate sample replacement and expand the caching capacity to 37 or 38 slots (see Section 6.2.3 and 6.3.2.3 for details). The proposed threshold sampling capacity for the Mars 2020 mission would be approximately 31 samples. The 31 sample value is based upon replacement capability of zero previously cached samples (see Section 6.2.3 for details). The baseline and threshold values represent the number of core samples that could be acquired by the drill/sampling system. These samples may or may not be cached.

<u>Capability to sample rock</u>. The SDT followed previous SAG and working group proposals that the 2020 mission <u>must</u> have the capability to acquire a core from rock/outcrop. The ability to acquire a regolith sample would be highly desirable. The same coring system may be used to acquire regolith material, but details (requirements) to obtain regolith sample(s) are left to the 2020 project office.

<u>Capability to acquire set mass/volume of rock/regolith sample</u>. Sample mass has received considerable attention from previous SAGs and WGs. The 2020 mission supports the previously published baseline and threshold mass values of 15-16 g per sample; which has been judged to be sufficient to accommodate laboratory characterization on returned samples for preliminary examination, planetary protection measurements, scientific research (destructive and non-destructive techniques), replicate analyses and reserve for future research (similar to the Apollo sample protocol). The rationale for the 15-16 g requirement is presented in the E2E-iSAG report (E2E-iSAG, 2012). The SDT also suggests a mass baseline and threshold value to collect 15-16 g of material. Mass measurement on Mars by the 2020 mission would be a technological challenging task that would require resources and drive complexity to the mission. Volume can be used as a proxy for mass. The SDT suggests the baseline/threshold capability to collect approximately 8 cc of material per sample. The 8 cc value is based upon the need to collect 15-16 g of material and assumes an average sample density value of 2 g/cc. The density would be highly variable depending on sample type, i.e., regolith vs. sedimentary rock vs. igneous rock, and the packaging of the sample in the sample tubes. The cores may fracture and leave large pore/voids between core pieces that result in an overall reduction in sample bulk density. The 8 cc volume is only an approximate volume. The SDT suggests that the value be further examined by the 2020 project office to determine what volume best meets the requirement to obtain 15-16 g of material per sample.

Additional sampling system attributes. Several additional attributes were not discussed by the 2020 SDT (fidelity of knowledge or axial/rotational orientation of core, cross contamination). These attributes, although important, were deemed of lower scientific priority and deferred for discussion by the 2020 project office. The baseline values established by previous WGs and SAGs are sufficient to address the scientific objectives for the 2020 mission.

Table 6-1. The key science attributes of the proposed sampling system

Attributes of the Sampling System			
Parameter	Historical	SDT	
	Baseline	Baseline	Threshold
HIGH-IMPACT AREA FOR SDT CONSIDERATION			
Minimum required depth of sampling	2 meters "scientifically desirable" (E2E, JSWG) >50 mm depth (MSL Heritage)	>50 mm	50 mm
Precision to which degree of filling of each sample tube can be measured or verified in the field	±25% (E2E)	25% of 8 cc	25% of 8 cc
SDT ADOPTED REQUIREMENTS FROM PREVIOUS STUDIES			
Capability for # of Samples to be acquired for caching or potential caching (Includes: Rock, regolith and/or dust, Blanks/standards)	38 (E2E, JSWG)	37 or 38*	31
Capability to sample Rock	Core (E2E, MSR-SSG, JSWG)	Yes	Yes
Capability of the sample tubes to acquire xx volume per rock sample	8 cc (E2E)	8 cc	8 cc
Capability of the sample tubes to acquire xx volume per regolith sample	8 cc (E2E)	8 cc	8 cc
Fidelity of knowledge of axial orientation of sample cores	High	TBD	TBD
Fidelity of knowledge of rotational orientation of sample cores	Low (picture only)	TBD	TBD
Cross Contamination	1%	TBD	TBD

6.2.1 Sampling Depth

Sample depth into rocks, outcrops, and soils on Mars to minimize "weathering" of organic molecules by ionizing radiation has been a hotly debated topic for years. Drilling remotely on a planetary surface is technologically challenging, especially drilling for depth into rock. The capability to retrieve samples from 2 m depth is highly desirable to protect changes by bombardment of galactic cosmic rays over time (Dartnell et al., 2007; Pavlov et al., 2012). However, recent studies suggest that it may be possible to sample materials where organic molecules are preserved by drilling only a few cm into rock or outcrop. Pavlov et al., 2012 used modeling to show that materials exposed by "fresh" craters that are no more than 10 million years old may still have organic molecules. Those "freshly" exposed materials have been near the surface for a short enough period of time that its overall exposure to harmful radiation would not have been long enough to destroy organic molecules.

Several study groups have stated that acquiring samples from 2 meters depth or greater is "scientifically desirable." Significant progress developing drills for the 1-2 meter depth range has been achieved in recent years, for planned and proposed missions (Magnani et al., 2010; McKay et al., 2013). However, given the difficulty in obtaining samples from those depths, this is not proposed for this mission concept.

Drilling to depth is challenging and would require considerable additional resources not likely to be available on this mission. Mars Science Laboratory ended up incorporating a powder drill that obtained a depth of 50 mm into rock. MSL initially considered a drill of >100 mm, but the project realized that a drill with this capability was a technological challenge and would require additional resources.

The SDT offers baseline and threshold values of >50 mm and 50 mm, respectively, into rock. The capability to drill deeper into a rock than 50mm would enhance the chances of organic molecule survival, so deeper into rock is better. The SDT suggests that the 2020 project office evaluate depths greater than 50 mm (deeper is better); however, there is a point where the resources and complexity required to go deeper would impact mission resources and success. Sampling strategies such as locating fresh bedrock exposed by an impact crater may provide the opportunity to sample materials that have not been exposed to long-term ionizing radiation and thereby preserve organic materials.

Finding 6-1: The minimum threshold depth for coring into rock is 50 mm. The baseline depth for sampling into rock is >50 mm. Sampling strategies, e.g., fresh "bedrock" exposed by impact, may provide opportunity to sample "deeper" than 50 mm where organic material may be preserved from ionizing radiation.

6.2.2 Field Verification of Degree of Filling of Sample Tubes

It is desirable to understand how much sample has actually been acquired in each drill core tube, as this would affect operational choices to cache, discard, or re-sample at a given location. This is phrased as the Field Verification of Degree of Filling of Sample Tubes. There are many options to define Degree of Filling - % of desired sample volume, % of desired or actual sample mass, absolute volume, absolute mass, etc. Field Verification methods could include optical, mass balance, or contact measuring techniques. The accuracy of any measurement would be greatly affected by the amount of porosity and void space in the acquired sample, and diametrical and linear variances. To reduce the potential implementation complexity, a coarse value of 25% of the desired 8cc of sample has been selected as the threshold requirement for this measurement accuracy. Stated alternatively, it is desired to determine within 2cc (25% of 8cc) the amount of acquired sample in each drill core tube.

Finding 6-2: The capability to determine to within 25% of 8 cc (i.e., within 2 cc) the amount of sample in the drill core tube is the threshold requirement.

6.2.3 Caching system

The intent of the caching system is to package samples (cores and regolith) in a manner suitable for possible return to Earth. Several attributes deemed to have high impact on the sample science are discussed in detail, including number of samples to cache, capability to replace previously cached samples, and encapsulation of samples (Table 6-2). That discussion is presented in the next three sections.

Several attributes were lower science priority and deferred for discussion to the Mars 2020 project office (Table 6-2). Those are briefly mentioned here. Witness plates[8] and/or blanks[9] would almost certainly be

[8] Witness plates – small coupons of appropriate spacecraft material used to collect the organic (including biological) contaminants that the spacecraft components would experience from fabrication to final assembly and sealing prior to launch.

[9] Blanks – small organics-free blocks (up to three) that are carried by the spacecraft to Mars and that will be cored and cached for return to Earth. These blocks will experience the same coring and caching process experienced by the martian samples. Any organic matter found in these blanks will most likely reflect terrestrial organic (including biological) contamination.

included on the Mars 2020 payload. Witness plates and blanks are critical for defining terrestrial contamination, especially for biological-related investigations. Their selection could be made later in the design of the spacecraft, selection of instruments. Witness plates and blanks are briefly described in Section 6.3.4.1.

The Mars 2020 mission cannot place stringent temperature constraints on the cache system. The mission concept is designed to operate on the surface for one Mars year (prime mission) and no date has been set to return the samples to Earth. It is unrealistic to place temperature constraints on a rover that may or may not be operating after the prime mission. The rover may last for years beyond the required design life. A best effort to place the sample in an area on the rover that would experience the least amount of temperature swings (i.e., high temperatures) is desirable, but not required.

Table 6-2. The key science attributes of the caching system

Attributes of the Caching System				
Parameter	Historical		SDT	
	Baseline	Threshold	Baseline	Threshold
HIGH-IMPACT AREA FOR SDT CONSIDERATION				
Number of Samples	31 (ND-SAG, E2E, JSWG)	19? (MPPG)	31	31
Rock, regolith and/or dust	*28*			
Blanks/standards	*3*			
Capability to replace cached samples	7 (E2E)	N.S.	YES 25% or expanded cache	NO
Samples separately encapsulated	YES (ND-SAG, E2E, MSR-SSG)	YES	YES	YES
Sample encapsulation spec (e.g., seal leak rate)	N.S.	YES	1 x 10^{-7} atm-cc/sec	No particulate transfer
SCIENCE ATTENTION LOW PRIORITY AT THIS TIME				
Witness plates	N.S.	Defer to project or successor science team to evaluate		
Blanks	N.S.	Defer to project or successor science team to evaluate		
Maximum Sample temperature while cache is being carried by Mars-2020 rover.	N.S.	Cannot predict capability of how long 2020 will be functioning		

6.2.3.1 Number of Samples to be Cached

Previous SAGs and WGs have proposed approximately 31 samples to be cached (ND-SAG, 2008; E2E-iSAG, 2011; JSWG, 2012). That number is based on several factors. Five hundred grams of material has long been argued as a baseline mass for the first sample return (MacPherson et al., 2002; E2E-iSAG, 2011). Rock samples of 15-16 g are deemed sufficient to carry out a research/PP program on returned samples (500 g ÷ 16 g = 31 samples). A number of samples are required to characterize a site. That number is dependent on the complexity of the geology of the site. E2E-iSAG (2012) estimated that 30-40 samples would be needed to characterize a complex geological site using Gusev crater as a case history (E2E-iSAG, 2012). Another important consideration is packaging geometry (Fig. 6-1).

The 2020 SDT supports the previous proposals of baseline and threshold values of 31 samples in the cache (E2E-iSAG, 2011, JSWG, 2012). The cache packaging geometry is ideally suited for 19, 31, 37, and 55 (see Fig. 6-1); however, there may be other more efficient packaging geometries that the 2020 project office may consider during design of the cache. Based upon the Spirit experience in Gusev crater, about 30 samples would be required to characterize the diversity of materials encountered in the first Mars' year of operations. The 31 sample cache size is an adequate number of samples to address the

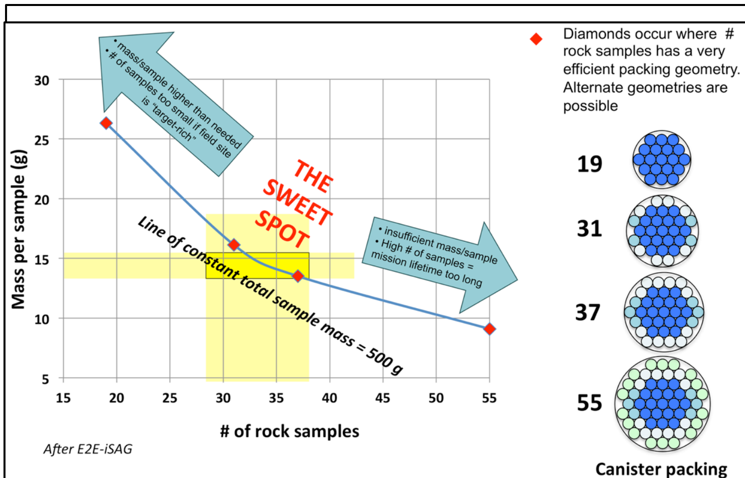


Figure 6-1. To bring back 500 g of sample of a particular size, particular packing geometries are possible*. E2E-iSAG (2012) proposed 500 grams for the total returned sample mass. Blue line shows the tradeoff between the number of samples and the mass of each. E2E-iSAG (2011 further proposed that each returned sample be ~ 15 grams to accommodate anticipated analyses on Earth (light yellow). The intersection of that shading and the constant mass line defines the 'sweet spot' of sample number & mass (in dark yellow rectangle) of 28 – 38 individual samples. Diamonds indicate efficient sample packing in a cylindrical return canister. After Figure 7 of E2E-iSAG (2012).*

science objectives outlined in Section 3 and to provide the opportunity to cache blanks or witness plates (see Section 6.3.4.1).

> **Finding 6-3:** The threshold caching capacity is 31 samples.

6.2.3.2 Capability for Replacing Previously Cached Samples

An important potential sampling-related functionality for the proposed Mars 2020 rover is the ability to replace previously collected samples with later ones. As the geologist walks a field site, the backpack becomes full of samples; hence, a "less" scientifically valuable sample is replaced with a higher value sample. The capability to replace cached samples would facilitate decision-making on the collection of samples early in the mission, prior to understanding the geology of locations that have not yet been visited (and with the practical consideration that the rover would almost certainly not be able to justify many, if any, reversals in its exploration pathway to go back to previous sites).

However, this replacement functionality does not become relevant until all of the slots in the cache are occupied, and there is no room for the next sample. An early, lower-value sample could simply be ignored in the cache until the cache is full, and there exists a higher priority need for the space. Prior thinking on this (E2E-iSAG, 2012) was that it would be prudent to be able to replace approximately 25% of previously cached samples. For a sample cache capacity of 31 cells (and if 3 slots are assumed to be standards, that leaves 28 slots for natural samples), that would mean that 7 cells could be replaced. Alternatively, if the cache were set up with an excess capacity, this would mean 38 slots (i.e. 31 + 7). The SDT has found that evaluation of excess sampling capability can only be done in the context of an analysis of the operations scenario, and in light of the assumptions/constraints relating to the state of the cache at the end of the prime mission or afterward. For this reason, further discussion of this topic is deferred to Section 7.9. The SDT notes that 37 is one of the close-packing geometries shown on Figure 6-1, and if that is necessary for reasons of engineering implementation, the scientific value of 37 samples cannot meaningfully be distinguished from 38 samples.

> **Finding 6-4:** The capability to replace ~25% of previously cached samples OR expand the number of slots in the cache to 37-38 (allows 6-7 slots for "excess" capacity over a 31-slot cache without replacement) is baseline. Threshold capability is NO replacement of previously cached samples or extra capacity for samples (i.e., 31-slot cache).

6.2.3.3 Sample Preservation/Curation

The discussions above have described the number and size of samples needed to address the high priority science objectives for Mars sample return. However, the number and size of samples is only sufficient if the scientific usefulness of the samples is preserved. A number of factors have the potential to degrade the scientific usefulness of the samples between the time they are collected and the time they are analyzed (see Fig. 6-2). E2E-iSAG (2012) concluded that the single most important factor in preserving the scientific integrity of samples during the interval between their collection and their analysis is effective encapsulation and sealing of each sample (E2E-iSAG, 2012).

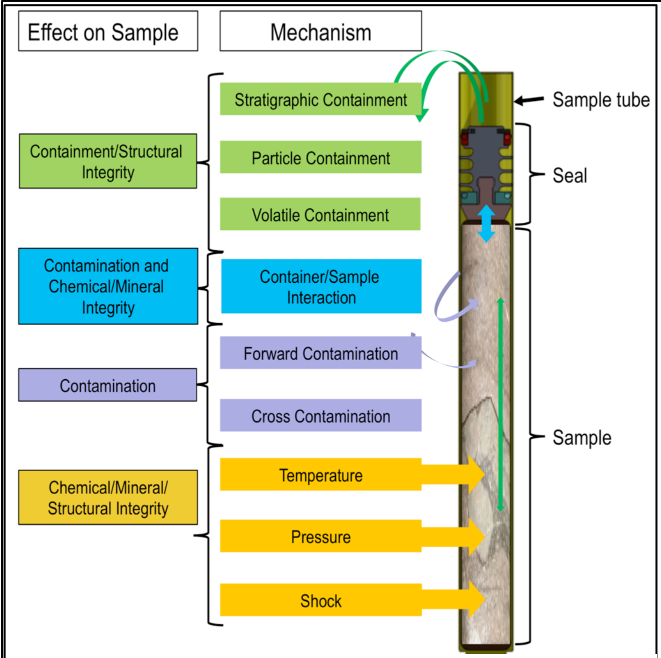


Figure 6-2 Properly designed, sample encapsulation would allow a sample to stay on the surface of Mars for a significant duration. *Proper leak-resistant containment would: enhance the integrity of the sample (chemical, mineralogical, and structural); greatly reduce contamination (cross, and forward) and enhance sample integrity by limiting gas and particulate exchange between the sample and sample encapsulation tube exterior*

Encapsulation as described here means the packaging of each individual sample into a container that could be used to identify it, protect it from exchange with other samples, and protect it from exchange with other elements of the flight systems. This allows each sample to be matched to its collection location on the martian surface. Therefore, we suggest a threshold requirement of "sample encapsulation to prevent solid particle of the transfer" to be sufficient for most scientific needs.

Sealing means closing the sample capsules to prevent a specified leak rate. Sealing isolates the samples, preventing the loss of material and volatiles, the addition of contaminants, and cross-contamination between the samples.

The requirement for the leak rate can be estimated by determining how much of the material of interest can be lost (or added) without affecting the science and over what period of time this leak rate should be planned. For Mars sample return the key volatile is water. If we assume loss or addition of less than 0.1% of the water content of the samples is sufficient to prevent significant changes (by analogy to the specifications for inorganic contamination from Neal et al. (2000)), we can then derive a leak rate. Please note that the 0.1% specification should be reexamined by the project science team as it may be more restrictive than necessary.

Finding 6-5: A threshold-level requirement to preserve the scientific value of cached samples is sample encapsulation and sealing.

Finding 6-6:
A) (Draft baseline) Sample sealing to within a gas leak rate of 10^{-7} atm-cc/sec He would preserve as much scientific value as possible.
B) (Draft threshold) Sample encapsulation to prevent solid particle transfer appears to be sufficient for most scientific needs.

6.3 Contamination

An important aspect of assessing the organic and inorganic chemistry, mineralogy, and other sample characteristics is to understand terrestrial contamination and environmental conditions that may impact measurements back on Earth. A high impact area for science is organic contamination of samples. Although inorganic contamination, exposure of samples to magnetic fields, and maximum temperature experienced by samples are important to sample integrity, these attributes are adequately addressed by the baseline values established by previous SAGs and WGs (Table 6-3).

Table 6-3. The key science attributes for maintaining the scientific integrity of samples that are cached.

Assumed Requirements related to Sample Integrity			
Parameter	Historical	SDT	
	Baseline	Baseline	Threshold
HIGH-IMPACT AREA FOR SDT CONSIDERATION			
Maximum Organic Contamination of samples	40 ppb (OCSSG), 10 ppb (MSR-SSG)	10 ppb	40 ppb
SCIENCE ATTENTION LOW PRIORITY AT THIS TIME			
Inorganic Contamination of Samples	For major and minor elements, 0.1% of concentration in Shergottites (MSR-SSG, 2005)	Defer to project to evaluate	
Exposure of samples to magnetic fields	desire 0.2 mT (MRR-SAG); no understanding that this is possible	Defer to project to evaluate	
Maximum temperature experienced by samples	T < 50C (MSR-SSG), 20 C (ND-SAG)	Defer to project to evaluate	

Four questions on the impact of contamination on the integrity of the samples and impact on the 2020 mission are addressed in this section:

1. What is the vulnerability of the different proposed Mars 2020 objectives to contamination?
2. How specifically does contamination affect the objectives?
3. Since contamination is inevitable, what are our strategies for dealing with contaminated samples, and how effective are they?
4. How clean is clean enough, i.e., what are the proposals for quantitative contamination control specifications?

Requirements that address these questions are essential to preserving the 2020 science objectives.

Note: This section of this report constitutes an analysis of the implications of contamination for achieving the charter-specified scientific objectives of the Mars 2020 mission. The SDT recognizes that contamination control is also an important issue for planetary protection. However, since we don't know a priori which of science and PP would have more demanding requirements, it is important that the drivers in these two areas be thought through independently. The analysis in this report relates to science only. The merging of planetary protection and science needs/constraints/policies to derive project-level contamination control requirements is something that will need to be done by successor planning teams.

6.3.1 Sensitivity to Different Contaminant Types

The mission's proposed objectives A, B, C, and D have very different degrees of vulnerability to contamination, and to different types of contamination. Objective A (Explore an Astrobiologically Relevant Ancient Environment on Mars to Decipher its Geological Processes and History, Including the Assessment of Past Habitability) does not require the cleanliness that Objectives B (Assess the

Biosignature Potential Preservation Within the Selected Geological Environment and Search for Potential Biosignatures) and Objective C (Demonstrate Significant Technical Progress Towards the Future Return of Scientifically Selected, Well-Documented Samples to Earth). For the purpose of Table 6.4, contaminants are defined as extraneous material that would interfere with the accurate measurement of what is in the sample. As will be shown below, the cleanliness requirements for Objective C are more stringent than Objective B. The cleanliness of samples in objective C are more stringent because samples returned to Earth may be analyzed by instruments that have several magnitudes of lower detection level capabilities. Hence, vulnerabilities related to later Earth-based analyses are accounted for under Objective C. Objective D does not require the degree of cleanliness as Objectives B and C.

The SDT identified the relative sensitivity of the 2020 mission objectives to different contaminant types (Table 6-4). The vulnerability of Objective C was rated "Very High" for Earth-sourced organic contaminants. The impact of this finding to the 2020 mission will be addressed in the following sections.

Table 6-4. Life detection measurements using returned samples are highly sensitive to Earth-sourced organic contaminants on the samples. *Vulnerability of the 2020 mission objectives to different contaminant types/sources*

Proposed Mars-2020 Objectives	Vulnerability to			
	Earth-Sourced Organic Contaminants	Mars-Sourced Organic Contaminants	Earth-Sourced Inorganic Contaminants	Mars-Sourced Inorganic Contaminants
Objective A	LOW	NONE	NONE	NONE
Objective B	MEDIUM	NONE	NONE	NONE
Objective C	VERY HIGH	LOW	HIGH	LOW
Objective D1	NONE	NONE	NONE	NONE
Objective D2	NONE?	NONE?	NONE?	NONE?

Finding 6-7: The most stringent science-related contamination issues relate to Objective C. If Objective C's needs are met, all other objectives can be achieved.

6.3.2 How does Contamination affect the 2020 Objectives

For Objective C, the effect of contamination is manifested by transfer to the samples, which are the vector for transport to high-precision, low detection limit sample analysis instruments on Earth. The following three implications are driven by these cleanliness requirements for Objective C:

- The part of the spacecraft that needs to be kept most clean (for science purposes) is the sample transfer chain.
- The only contamination on sample-contact surfaces that matters to sample-related science is the fraction that transfers to the samples. There is no pathway for non-transferrable contaminants to affect this kind of measurement.
- For the purpose of science planning, the contamination requirements need to be defined from the point of view of the sample, not from the point of view of spacecraft surfaces. The former directly affects measurements, the latter does not.

Finding 6-8: For the purpose of Mars 2020, the driving contamination requirement relates to that which is potentially transferred to a sample, especially the cached samples, and by that means might be transported to an instrument that can detect it. Non-transferrable contaminants do not interfere with the scientific objectives proposed.

6.3.3 High-Level Strategy

It is impossible to clean spacecraft surfaces of all organic molecules. The SDT recognizes that impossibility. Samples analyzed on Mars and those returned to Earth will have some Earth-sourced organic contamination on them. For any samples returned from Mars to Earth, it must also be assumed that there is a nonzero likelihood that they will contain extant living martian microorganisms (NRC 2009). As such both forward and backward contamination issues are related to the terrestrial organic matter contamination borne by the Mars 2020 rover and have been considered in developing a strategy to deal with it. Because Mars 2020 rover will not be sent to a special region as defined in SR-SAG (2006) and because Mars 2020 will not be carrying instruments designed to detect extant life it will not be necessary to reduce the overall bioburden of the spacecraft to Viking spacecraft levels. Nonetheless, the samples cached for return to Earth will be subject to life detection experiments and any terrestrial organic contamination borne by these samples should be at such a level that it does not undermine the scientific goals of MSR. The release of samples from a Sample Return Facility will be contingent upon insuring that the samples do not contain biological entities that represent a threat to Earth's inhabitants or environment (NRC 2009). As such if terrestrial biological entities or the organic constituents thereof are detected in the returned samples, then it is important that they are not mistaken as being martian (false positives) and perceived as a threat, thereby resulting in the quarantine of the samples.

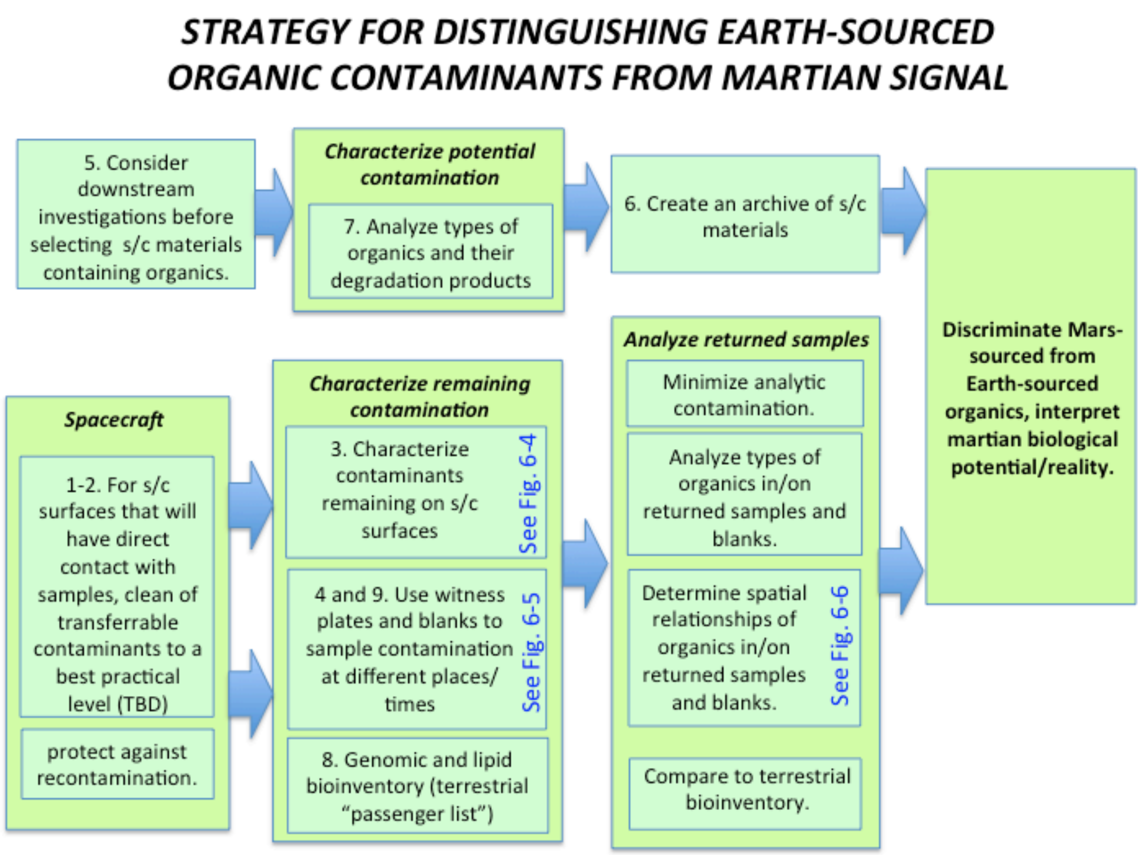


Figure 6-3. Summary of the proposed strategy for distinguishing Earth-sourced organic contaminants from martian signal. *Includes defining and cleaning spacecraft surfaces that come in contact with samples (1-2), characterizing the remaining contaminants using witness plates and blanks (3, 4 and 9), selecting and characterizing the organic-bearing components of the spacecraft that come in contact with the sample (5-7) and creating an inventory of terrestrial organisms carried by the entire Mars 2020 rover.*

With this in mind and because it is difficult to predict exactly how different types and quantities of contamination would impact future science investigations of the samples cached by this mission, the SDT proposes a conservative three-step strategy to mitigate the potential deleterious effects of terrestrial organic contamination (Fig. 6-3). First, it is imperative that terrestrial organic contamination be monitored and minimized in order to assess how and to what extent sample integrity may be compromised by terrestrial contaminants. Second, the potential organic contaminants that remain after the first step must be characterized in detail so that their presence can be clearly recognized and considered in the results of organic matter investigations of the cache samples upon their return.

A high-level strategy for minimizing and monitoring for organic matter contamination involves 10 steps (Fig. 6-3):

1. Define the realistically achievable contamination level that would still allow us to achieve Objective C (see Section 6.3.2 for discussion).
2. Implement hardware processing procedures that are certified to produce that level of organic matter cleanliness for the sampling, delivery, and caching chain, as well as for the rest of the spacecraft. In addition, provide for procedures to ensure that the sampling, delivery and caching systems are not recontaminated during post-assembly transport, launch and cruise to Mars.
3. Standardize techniques for verifying organic matter contamination levels during the hardware build process and after major component integration. The goal of this approach is to allow for re-cleaning of components with minimal disassembly in the event that unacceptable levels are detected (see Section 6.3.4.1 for discussion).
4. Document the types and amounts of contamination for the entire sampling chain, from collection and delivery to *in situ* instruments and the cache before launch using witness plates (see Section 6.3.4.1 for discussion).
5. Consider downstream investigations before selecting spacecraft materials containing organics (see Section 6.3.4.1 for discussion).
6. Create a database of organic-bearing materials that are potential sources for contaminants (see Section 6.3.4.1 for discussion).
7. Perform experiments on organic-bearing materials under martian conditions to observed degradation products that could be transferrable and create a database of these products.
8. Create a database of potential biological contaminants that could be accessed by future investigators (see Section 6.3.4.1 for discussion).
9. Apply monitoring techniques (e.g. blanks) to document forward contamination by the Mars 2020 rover that would be captured by cached martian sample (see Section 6.3.4.1 for discussion).
10. Consider operations that reduce the opportunities of organic matter contamination from the Mars 2020 rover to the sampling surface and to perform *in situ* cleaning and mitigation and utilizing martian resources instead of onboard resources when possible (e.g., coring martian aeolian sediment or regolith to removed residual terrestrial organic contaminants from the inner surfaces of the coring tool).

Many of these elements have heritage from MSL and earlier missions. However some refining of these approaches would improve efficiency of the monitoring process as well as provide a much more detailed characterization of potential organic contaminant sources. Some of these steps should be specifically tailored to the sampling hardware and organic matter analytical techniques that would be used in the Mars 2020 science investigations.

Finding 6-9: It is impossible to clean spacecraft surfaces (and to keep them clean) to the point that they have zero Earth-sourced organic molecules. Thus, it is a certainty that returned samples will have <u>some</u> Earth-sourced organic contamination on them. **The real questions are how much contamination, and of what character is the contamination.**

Finding 6-10: The SDT suggests a two-part organic contamination control strategy for Mars 2020: a) collect and package samples as cleanly as is realistically achievable; and b) characterize the contaminants present below this "clean" level, so that the signal and the noise can later be distinguished.

Steps 1-3 involve cleaning all spacecraft surfaces that contact martian samples to a realistically achievable level (Fig. 6-3). MSL had stringent organic cleanliness requirements because of the organic matter detection capabilities of the Sample Analysis at Mars (SAM) instrument (Mahaffy et al., 2012) and thus serves as a starting point for a strategy for addressing terrestrial organic matter contamination. For MSL, materials used in the rover spacecraft that may result in the production and/or transport of contaminants to SAM were sampled and logged (Misra et al., 2012). Hardware was precision cleaned when possible. Prior to launch, a portion of the sampling chain was swabbed to collect particulates and any transferrable organics for a measure of post-rover integration contaminant levels by Fourier Transform Infrared (FTIR) analysis (Anderson et al. 2012a).

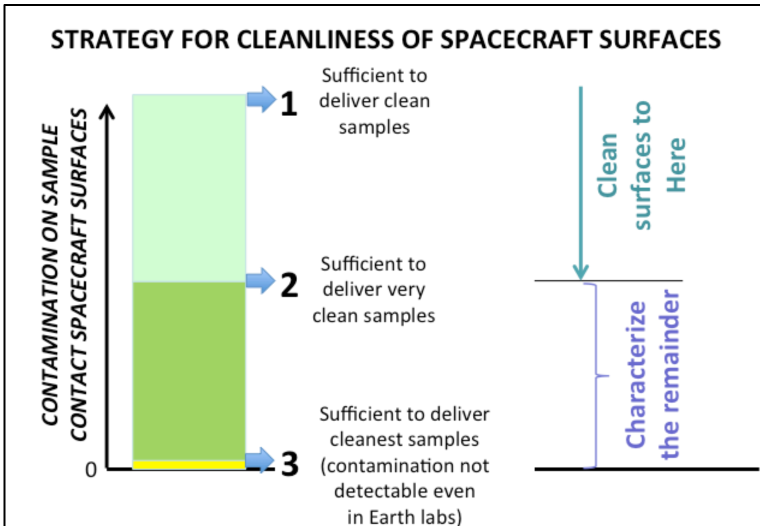


Figure 6-4. Cartoon of the strategy for dealing with organic matter contamination on spacecraft surfaces that contact samples on the Mars 2020 mission*. Earth-based laboratory instruments are able to detect organic matter at levels far below the levels to which we can clean and below the detection limit of SAM on MSL. The spacecraft surfaces would be cleaned to MSL levels consistent with SAM detection limits. The same strategy should be adopted for biological contamination.*

A key question is, "How clean is clean enough?" The SDT finds that the cleanliness levels of MSL should suffice to successfully achieve the Mars 2020 mission's Objective C. Cleaning to more stringent contamination levels would cost significant additional expense. However, since the organic matter analytical techniques that would be used to study cached samples would be highly sensitive to molecular and isotopic composition at highly resolved spatial scales it is more important than ever before, to thoroughly characterize any organic contaminants on surfaces that contact samples and log all potential sources of organic contaminants during the hardware build and integration.

Finding 6-11: Launching a spacecraft for which the sample coring and caching chain has been cleaned to a standard better than that of MSL:

a) Is possible but with significant expense
b) Would not eliminate the need to have strategies in place to recognize contamination on returned samples, since Earth-based detection systems have far lower detection limits than *in situ* instruments and other contamination pathways exist beyond the coring and caching chain.

6.3.4 Acceptable Organic Matter Contamination Levels

The degree to which interpretation of analyses of martian samples would be compromised by the presence of organic contaminants in samples containing indigenous martian organic material is unknown. Thus, we do not know what level of cleanliness would be appropriate. Contamination should be kept as low as reasonably possible and within the guidelines proposed by MEPAG OCSSG and the MSRSSG report. In these reports a total of **40 ppb** reduced organic compounds, with sub-allocations of 1-10 ppb for specific compound classes was proposed by OCSSG (2003) (this spec was specifically intended for *in situ* investigations, including MSL). The MSR-SSG-II (2005) proposed a total of **10 ppb** of reduced organic compounds, with sub-allocations for specific compound classes—proposed for at least some MSR samples. These figures are estimates only of contamination levels needed to achieve the science objectives. As discussed in 3.4.1.3.5, different levels may be required to meet planetary protection requirements, and those levels will be specified by advisory groups specifically chartered for that purpose.

Finding 6-12: Delivering samples to the cache that have <10 ppb (baseline) or <40 ppb (threshold) total of Earth-sourced organic carbon would be sufficient to achieve the scientific objectives of Mars 2020. Other standards may be required to meet planetary protection needs.

6.3.4.1 Strategies for Recognizing Contamination in Martian Samples – Blanks, Witness Plates and Spacecraft Materials

As mentioned in the previous section, it is impossible to eliminate terrestrial organic contamination from the Mars 2020 sampling and caching system. However, the success of any organic matter detection or characterization experiment is dependent on the knowledge of known and potential contaminants present. The better these contaminants are understood the more likely their negative impact on interpretations could be mitigated, potentially instilling greater confidence in interpretations. Leveraging techniques and strategies used for other missions (e.g. Stardust, Phoenix, and MSL), many contaminants could be detected and characterized during the hardware build process, hardware characterization and calibration, and during operation on Mars. Three strategies will be briefly described in this section – hardware surface tests and witness plates (steps 3 and 4), blanks (step 9), and selection and characterization of spacecraft materials (steps 5-7) and constructing a bioinventory of potential contaminating microbiota (step 8).

Hardware Surface Tests and Witness Plates. Most contamination on hardware could be mitigated by regular testing and cleaning of hardware components during the build process and after major component integration. Ease of implementation and information yield is supported by standardizing monitoring methods. Witness plates are useful in collecting samples of volatile and particulate organic contaminants (including biological contaminants) in the air adjacent to hardware during fabrication and assembly. Witness plates do not record all hardware surface contaminants. Both cleanliness verification to acceptable levels (Fig. 6-4) and characterization of organic and biological contaminants requires analysis of these contaminants on hardware surfaces by either direct measurement (e.g., spectral imaging) or by transfer of contaminants to other media for analyses (e.g., solvent rinses or swabs of surfaces that are further processed for measurements). Because no one measurement technique detects and broadly characterizes all types of organic contaminants, the SDT suggests that verification of organic matter cleanliness should include characterization by instruments similar to those of the *in situ* payload. Biological characterization should comprise metagenomics and lipidomics of the particulate organic matter.

Blanks and Standards. Blanks and standards are routinely analyzed in laboratories to determine the amount of contamination. For example, Phoenix flew an organic-free ceramic blank that was to be used to characterize the cleanliness of the sampling system if organic molecules were detected by the Thermal Evolved Gas Analyzer (Ming et al., 2008). MSL has 5 fused silica bricks (Conrad et al., 2012). These blank (negative control) materials require specialized handling to maintain their purity until the time of sampling. In order to document the types and amount of organic contamination that may be introduced to cached samples, without any confusion with potential martian contributions, organic check material **must** be processed through the sampling chain on Earth as a prelaunch characterization of the flight hardware

(Fig. 6-5). A similar approach must be applied to the characterization of biological contaminants as stated in the preceding strategy and a determination of the bioburden reduction level provide by the cleaning methods. Analyses of the processed organic check material should compare surface deposited contaminants to contamination in the material's interior. Results would inform both *in situ* and sample return investigations and the processed organic check material could be archived for future use. Analysis of this archived initial organic check material can be performed using the same organic matter characterization techniques not only used during the Mars 2020 mission, but also during subsequent analyses of the returned samples. In addition to its use to document terrestrial contamination up to the launch of the mission, organic check material cached after sampling martian materials would capture an organic matter signature for the integrated effects of contamination imposed by pre-launch, cruise and rover operations.

Past studies have assumed that in a 31-slot cache, at least 3 slots would be reserved for blanks (E2E-iSAG, 2012). Specific strategies for the design of the blank, and when and how they would be used, have not been developed and would need to be examined by the Mars 2020 project office. The SDT suggests that the cleanliness of the blanks be verified pre-launch using, at minimum, flight-like analyses.

Spacecraft Material Choices and Documentation. It is crucial to know what contamination might be contributed to samples from spacecraft materials and that materials are selected to minimize potential transfer to the sampling chain and cached samples. Organic carbon containing materials that are commonly used for spacecraft, such as Teflon, Kapton tape with acrylic adhesive, Braycote lubricant, may be adequate for some applications, but have the potential of being detrimental to studies of martian organics *in situ* or upon return to Earth. For example, Teflon, which is generally regarded as having low chemical potential as an organic contaminant, was found to be a contaminant in rock powders due to abrasion in the MSL drill bit assembly, adding some complication to organic matter analyses by the SAM instrument suite (Eigenbrode et al., 2013). The potential for compromising science for objective C of the Mars 2020 mission is much greater than for MSL as the cached samples will be scrutinized by high-resolution molecular, isotopic, and imaging instruments with much greater sensitivity than SAM upon their return to Earth (Section 6.2.4.6). Materials used for storing samples need to be designed to tolerate ionizing radiation for decades. Thus, before design review, it is important that the stability and potential transfer of all organic materials and their volatiles be re-evaluated, in terms of their potential to introduce trace levels of contaminants to samples and how these contaminants might be measured during investigations of cache samples. Suitable alternatives to organic materials or substitution with organics materials that could be easily tracked should be used when possible.

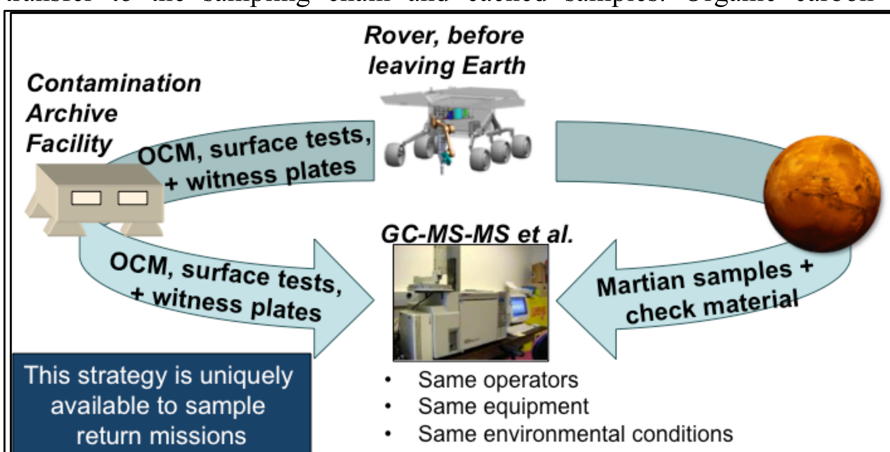


Figure 6-5. Levels and composition of organic matter related to samples returned to Earth could be compared to the levels and composition of organic matter originally sent to Mars. *Strategy for recognizing contamination in Mars samples using witness plates and swab samples in the contamination archive facility along with organic check blanks flown and returned from Mars.*

Biological Contamination Documentation. An unknown proportion of the terrestrial organic contamination that will be present on the returned samples will be comprised of the cellular constituents of terrestrial microbiota, perhaps even intact slots. These microbiota may originate from the spacecraft assembly facility for the Mars 2020 vehicle, from the Mars Sample Return mission (rover and MAV), or from the landing site on Earth (if the seals are breached). At every step of its journey the potential biological contaminants of the Mars 2020 cache will need to be characterized. Thanks to recent advances in molecular analyses and bioinformatics the means exist to characterize the complete genomes of those organisms contaminating the surfaces of the spacecraft during assembly. Previous studies of these environments have revealed a low diversity bacterial community comprised primarily of human commensal and desiccant-resistant bacteria with a surprisingly low abundance of spore formers (Moissl et al. 2007). The low diversity of this potential bioburden (although further surveys of viruses, Archaea and Eukaryotes need to be performed) means that fairly decent sequence coverage of the whole genomes and viromes of the microbial community is attainable on present day sequencing platforms. The genome sequences would provide the amino acid sequences of the proteins, which comprise over 50% of the biomass in the case of bacteria. Besides the nucleic acids and proteins the other important cellular constituents are cell walls and lipid membranes and mass spectrometric approaches currently exist for the characterization of both of these constituents. Over the next decade the sensitivities and throughput of all of these approaches will continue to improve and will become increasingly utilized for Planetary Protection studies. A searchable database of metagenomic and virome sequences and lipidomics structures (such databases already exist) would provide a diagnostic tool for detecting terrestrial biological contamination when these same methods are applied to the samples and blanks returned from Mars (Fig. 6-5).

Finding 6-13: All organic materials selected for incorporation in the hardware of the sampling chain and elsewhere in the rover require evaluation of their potential impact on the specific science measurements made *in situ* and upon the cached samples. The initial composition of the organic materials, outgassing volatiles, radiolytic degradation products, and particulate shedding must be considered.

6.3.5 Strategies for Recognizing Contamination in Martian Samples

6.3.5.1 The Position of Organics in/on the Sample

The location of organic molecules on/in the sample(s) and with respect to host mineral assemblages at the microscopic scale will provide crucial insight into the origin of these organic molecules (whether terrestrial contamination versus martian). Organic molecules located in the rock core interior may have a very different meaning than the same molecules found on the surface of the core. Surface removal or excavation (e.g. Ion Beam Milling/sputtering) combined with microanalytical capabilities (e.g. nanoSIMS or TOF-SIMS) will be essential technologies for the analyses of returned samples. A good example of application of this principle is shown in Figure 6-6.

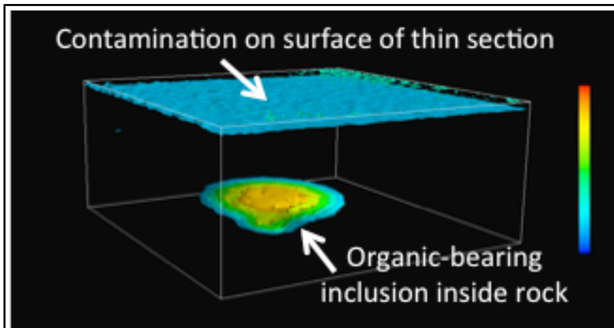


Figure 6-6. Three-dimensional representation of organic molecules in a thin section. *Data show m/z 55.06 signal strength collected during high mass resolution profiling of area (100x100 µm2) Z direction (2.6 µm). The top blue side of the cube is the contaminated surface of the thin section, and the blue to orange sphere is an oil-bearing fluid inclusion in the interior of the rock. Red indicates the strongest signal intensity while blue is the weakest. The sample is from the 1.4 Ga Bessie Creek sandstone from the Borrowdale drill hole in the Roper Group in Western Australia. After Siljeström et al, 2010.*

Finding 6-14: A key strategy to distinguish Earth-sourced contamination from martian signal is analyzing whether the organic molecules are located in the rock interior or on the rock's surface.

6.3.5.2 The Tissint Case History

Martian organics have been previously detected in meteorites (Grady et al., 2004, Steele et al., 2007, 2012a, b, 2013, Agee et al., 2013); however, the fall of the Tissint meteorite provided a unique opportunity to study a minimally contaminated piece of Mars for the presence of organic carbon as a rehearsal for sample return. Tissint is a geochemically depleted picritic shergottite similar to EET79001 (Aoudjehane et al., 2012). Nearly 2 dozen analytical instruments were used to characterize ~1.3g of sample. Confocal Raman Imaging Spectroscopy (CRIS) has shown the presence of inclusions in maskelynite that contain macromolecular carbon (MMC) similar in its characteristics to that found in other martian meteorites (Steele et al., 2013). CRIS maps correspond to maskelynite, magnetite, apatite, pyroxene, pyrite and MMC and occur approximately 5.4 μm under the surface of the section. Raman mapping confirmed the presence of similar pyrite, MMC and magnetite rich assemblages in 18 maskelynite bound inclusions in Tissint. High resolution-transmission electron microscopy images of Focused Ion Beam (FIB) milling through an inclusion indicate maskelynite surrounding the inclusion but with the interface delineated by a series of empty, rounded, bubble-like features and with additional voids inside the inclusion. Energy dispersive X-ray spectroscopy and Selected Area Electron Diffraction (SAED) confirmed the presence of anhydrite, magnetite, and Ni containing pyrrhotite. While the presence of magnetite was confirmed, the remaining Si, Al and Cl are in an as yet unidentified nano-phase that could possibly be Cl-containing aluminosilicates. Nano Secondary Ion Mass Spectroscopy (NanoSIMS) analysis of the inclusions showed the presence of C and N as well as Cl, P and S within these inclusions. Scanning/Transmission X-ray microscopy analysis of FIB sectioned inclusions analyzed by Raman and nanoSIMS showed a complex aromatic moiety containing no graphitic domains, but did contain a significant portion of C=C, C=O as ketone and carboxyl groups, C-O-H as ethanol and carboxyl groups, and possibly aliphatic carbon.

Analysis of the amino acid inventory of Tissint proved the presence of amino acids of terrestrial origin. Since the amino acid extraction was from a bulk sample of Tissint, the contaminating amino acids may be tied to the presence of small grains of carbonate from the Moroccan soil where the meteorite landed and comprised ~1.5 ppmC in total. Time-of-Flight SIMS investigations revealed the presence of CN^- and CNO^- associated with S and SO_2 at concentrations well above background levels. These analyses indicate that the Tissint meteorite has an inventory of organic C and N compounds indigenous to the meteorite.

The ability of modern instrumentation to undertake this level of analysis on such small sample sizes illustrates that the return of well-chosen samples to Earth would be of paramount importance to our ability to detect, characterize and interpret organic carbon signatures as PBS or biosignatures (as seen in Fig. 6-6). It also illustrates that even though the Tissint meteorite was seen to fall, recovered quickly and analyzed with the highest sensitivity instrumentation available it still contained a significant component of terrestrial organic contamination.

Finding 6-15: Multiple strategies are available to sample analysts to recognize Earth-sourced organic contamination in martian samples. As shown by meteorite studies, these can be applied even when the concentration of the contaminants exceeds that of the martian signal (although in such cases, detection capability is degraded).

6.4 Sample Processing/Transfer System

The proposed Mars 2020 rover would not have a sample processing system to crush and deliver samples to an instrument. The SDT realized that the complexity and resources required for a core crushing, powder sample processing (e.g., sieving) and powder sample delivery to an instrument appear to be beyond the scope (budget) for the Mars 2020 mission. Also, the cost of most sample instruments pushed the available payload resources outside the budgeted payload limit for the Mars 2020 mission. However, the suite of measurements proposed for the Mars 2020 mission may have the opportunity to observe cores, core drill tailings, or the core borehole during the mission. The attributes considered by the SDT are listed in Table 6-6. Only the attribute of observing a cored material (core, core drill tailings, and core borehole) with the instruments was examined for feasibility within the constraints of the Mars 2020 mission.

Attributes of the Sample Processing/Transfer System			
Parameter	Historical[1]	SDT	
	Baseline	Baseline	Threshold
HIGH-IMPACT AREA FOR SDT CONSIDERATION			
Delivery of uncrushed core to an instrument	TBD	Yes	No
SCIENCE ATTENTION LOW PRIORITY AT THIS TIME			
Rock/core crushing	TBD	No Sample Instruments	
Powder sample processing	<150 μm (MSL)	No Sample Instruments	
Powder sample delivery	TBD	No Sample Instruments	

Table 6-5. The key science attributes of the Sample Processing/Transfer System

6.4.1 Observing cored material with instruments

The caching objectives and architecture of the studied 2020 rover mission naturally lead to questions about any "real time" *in situ* science measurement requirements associated with coring and caching activities. In the threshold concept of operations, sedimentary outcrops or other high-priority targets are identified for detailed analysis with context and contact imaging and spectroscopic techniques. In the reference case, chemical analysis of an abraded surface may reveal the target to host a compelling distribution of features including indications of habitability, biosignature preservation potential, and/or potential biosignatures, such as the detection of organic compounds in spatial association with heterogeneously distributed low-temperature mineral deposits (veins, inclusions). Such measurements, in the context of all prior data and Mars science generally, at the time of the surface mission, are expected to be sufficient (in the threshold sense) for making the decision to extract and cache a core sample, *without further analysis* of the subsurface material at that sampling site. Even with this simplified triage concept, the SDT considered the mission well worth flying given the extensive environmental context data and fine-scale surface analysis that would still be available to interpret the analyses of the cores once returned to Earth.

Nevertheless, although core samples would be subject to excruciatingly detailed analysis back on Earth, there are several important reasons why it would be scientifically valuable to examine either the core or the walls of the hole while the rover is active in the field:

1. *Verifying that the core sample contains the desired material or features evident on the surface.* There are several available approaches to link what may be expected in the several cm-scale subsurface accessed by a drill core to what is observed on the abraded surface of the host rock. The composition of the surface itself can be taken as a first-order guess of the mean core chemistry and mineralogy. Fine-scale lateral surface heterogeneity, within the notional several-centimeter abraded diameter, may further suggest the variety of phases to be found along the core length. In addition, in a tilted horizon the material to be sampled "at depth" may be observable with only surface abrasion of nearby points. This could be modulated to some degree using different angles of attack of the abrasion and coring devices. Finally, one may be able to tell if fine compositional layers or gradients do exist in a core, using multiple applications of the abrasion tool. Variations in the

oxidation state of Fe in the Mazatzal basalt were observed by the Mossbauer spectrometer on MER (Morris et al., 2004) with repeated RAT grinds covering a depth of several mm. However, these links are incomplete, and it remains possible that critical aspects of core composition and layering, supporting both *in situ* science and sample return selection, may go undetected without direct measurement of the core surface itself, or perhaps the borehole walls.

2. *Supporting the time-critical process of selecting and prioritizing samples for analysis and caching, within the local geological context.* As mentioned in (1), direct observation has the potential to remove the uncertainty of the nature of the subsurface sampled by the core, without necessarily subverting the need for efficient operations. On the contrary, the crucial process of prioritizing core samples based on pre-defined criteria (to be determined by future science teams) is enabled by such examination of the exterior of the core or the "matching" borehole wall surface. For example, detection of significantly higher concentrations of organics in the deepest end-portion of a core, compared to the surface, may be undetectable with only surface examination, and yet would likely be a significant criterion for cache prioritization. In a limited-capacity cache scenario, it is possible that analyzing some or all of the cores (either "test cores" that precede the "cache cores", or the "cache cores" themselves) would be the optimal approach to prioritization "triage".

3. *Characterizing subsurface compositional variations in support of habitability assessment and potential biosignature detection.* Just as core or borehole wall analyses would enable enhanced information for caching decisions, such analyses would strongly support both habitability (Objective A) and potential biosignature (Objective B) science return. In particular, the convex exposed surface of an extracted core could be examined point-by-point by the full instrument complement available to probe rock surfaces directly, even those requiring an optical head to approach the sample at close working distance. Even a small number of such test cores could be sufficiently representative of the subsurface/bulk rock mineralogy and chemistry to help calibrate the larger set of surface analyses, and indicate what to expect in future cores. Examination of extracted cores or borehole walls opens a new and important dimension of science analysis for Objectives A and B.

4. *Ensuring scientific returns from coring activities even if the sample(s) are never returned to Earth.* This self-explanatory reason covers the optimal level of science return, as mentioned in (3), in the unfortunate scenario of no cache returned for whatever reason.

The implementation of core or borehole wall examination is mainly guided by relative feasibility of different potential steps. Some of the more difficult, if not impossible, activities include:

- Reliably getting a cache core out of its tube (into which it was acquired) without resorting to complications that could greatly slow operations or drive complexity;
- Acquiring an unencapsulated sample, observing it, then inserting it into a core tube (rather than coring the sample directly into the tube;
- Inserting "full" instruments or front-end optical heads into a borehole with cm-scale diameter. This is to be contrasted with potentially feasible borehole wall observations (see below).
- Integrating down-hole instruments behind the bit.

Despite such complexities in the "brute force" approach to core examination, alternatives that would be scientifically and technically feasible may include:

- Using existing instruments to examine bore hole walls from (i) outside the borehole, at some off-normal incidence, or (ii) a side-looking insertion probe, using fiber optical coupling of light into an arm-mounted spectrometer.
- Acquiring unencapsulated cores and making them available for observation by the contact instruments. Such a "test" core could be placed in an observation tray/fixture, ejected on the

martian surface, or retained in a dedicated bit geometry that allows surface access. This would be the extent of any payload-provided "delivery" an acquired core sample to an instrument; any further requirements would be the responsibility of an individual instrument.

Following examination, if there was a desire to cache such a sample, a second (encapsulated) sample would need to be taken.

Finding 6-16: The capability to observe cores in the field would support both cache sample selection and *in situ* science objectives, and is considered a baseline functionality. Observation of bore hole walls could also provide such support, and is also considered a desirable instrument capability.

6.5 Surface Preparation

Preparation of a rock surface is required to achieve optimal measurements of its chemistry, mineralogy, texture, and color characteristics. Removal of dust alone is insufficient given the likelihood of weathering rinds or surface coatings, as shown by observations from the MERs (Fig. 6-7). Thus, some means must be available to remove rock material beyond just brushing off dust. Surface preparation would be especially important to the 2020 mission because the rover would rely on remote and contact measurements rather than onboard lab-type measurements to achieve its objectives. Based on MER/MSL capabilities, some form of circular brushing and grinding is the expected means for surface preparation, but other more novel approaches may be viable. Grinding could serve as a preview to coring, providing useful information on rock hardness, as demonstrated by the MER Rock Abrasion Tool (RAT).

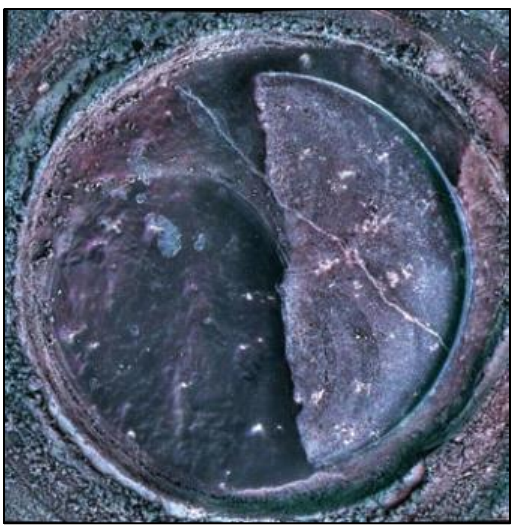


Figure 6-7. A dust free, cleaned and smoothed surface provides a better target for instrument measurements than an "as-is" surface. *Surface of martian rock (the basalt Mazatzal), brushed and partially ground by the Rock Abrasion Tool (RAT) on Spirit rover. Brushed and abraded circle is 45 mm diameter. Grayscale image from the MI camera, merged with color from Pancam imager. Left side is brushed only, and shows dark surface coating not present on abraded surface at right. Image c/o JPL/NASA/MSSS.*

Table 6-6. The key science attributes of the Surface Preparation System

Attributes of the Surface Preparation Tool			
Parameter	Historical	SDT	
	Baseline	Baseline	Threshold
HIGH-IMPACT AREA FOR SDT CONSIDERATION			
Surface prep tool - how much material to be removed (diameter, depth)			MER capabilities
Surface prep tool - how smooth the surface prepared?			MER capabilities
Surface prep tool - how clean the surface prepared?			MER capabilities

Major Finding 6-17: Rock surface preparation (dust and rock-material removal) is necessary to maximize *in situ* science results and select optimal samples for caching, especially given the reliance on remote and contact measurements expected for the proposed 2020 mission.

6.5.1.1 Surface Preparation: Depth and Diameter Considerations

The depth to which rock material must be removed to provide access to unaltered or less altered rock can be assessed from previous missions. As shown by both MERs and MSL, dust coatings on rocks are

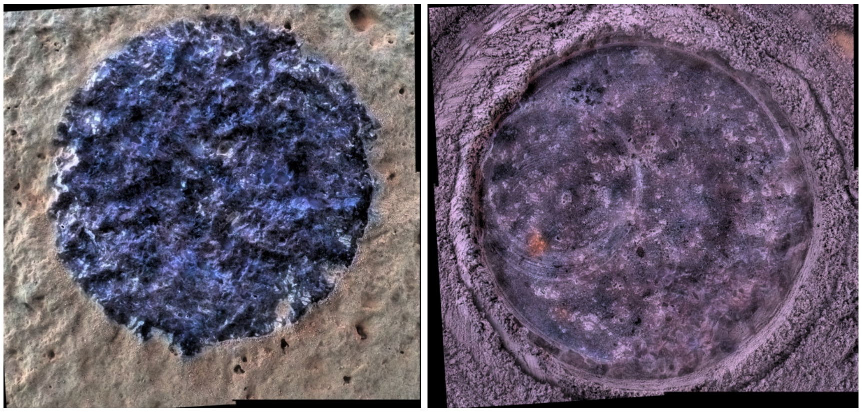


Figure 6-8. Apparent color change after dust has been removed from the surface of rocks. *Abraded/ground surface on the rock Humphrey at the Spirit site. The ground surface shows no obvious detritus related to the grinding operation, providing clear view of textural details of the rock and work surface suitable for interrogation by compositional instruments. Brushed and abraded circle is 45 mm diameter. Grayscale image from MI camera, merged with color from Pancam imager. Credit to JPL/NASA/MSSS*

readily removed by brushing only. Rock coatings encountered on Mars to date are less than ~1 mm in thickness, so represent a minimal demand for preparation depth. Alteration rinds can be much thicker, perhaps by a factor of ten. But this thickness is difficult to quantify, and complete removal of an alteration rind in some cases may not be possible or necessary. Based on MER experience, it is sufficient to document changes (i.e., chemistry, mineralogy, texture) with depth through a rind to ascertain the characteristics of the rind vs. the substrate. As shown by the MERs, alteration rinds can be characterized with grind depths <5 mm (Fig. 6-7).

There is no scientific demand for minimizing the prepared surface area; bigger is better. Ideally, the size of a prepared surface would be at least as large as the largest field of regard among the science instruments, but operational demands (time, power, instrument lifetime) are limiting factors. Lithologic features (e.g., pores/vugs, mineral grains, veins, concretions) may approach 1 cm in size and be heterogeneously distributed, so prepared surfaces several times this size should be the minimum requirement (i.e., 3-4 cm in diameter).

6.5.1.2 Surface Preparation: Cleanliness Considerations

As shown by MER experience (e.g., Squyres et al., 2006), there is scientific value in applying a protocol of surface dust removal followed by variable penetration into the rock (see Fig. 6-8). To achieve maximum benefit, dust and loose particles produced during grinding need to be removed at each step to create a visibly clean surface as viewed by a fine-scale imaging instrument. Such material also represents a contaminant for compositional measurements, including spectroscopy. Minimizing residual particles thus ensures a more accurate assessment of the prepared surface.

6.5.1.3 Surface Preparation: Smoothness Considerations

In order to properly discern rock textures following the removal of rock material, residual features on the rock surface from grinding or comparable operations need to be minimized (Fig. 6-9). In this case, smoothness relates to the absence of roughness elements that could be resolved by fine-scale imaging instruments. Demands by mineralogy/chemistry instruments related to smoothness also must be considered.

All optical instruments including Green Raman, deep UV Raman, and fluorescence instruments can have issues with surface roughness, angle of incidence, etc. Typically these issues are mitigated by incorporating line scanning capabilities in addition to a high F/#, focus tolerant design, low magnifications, high numerical aperture optics, and Z-stacking ability. These sorts of instruments have demonstrated high quality data with surface reliefs of ≤1mm.

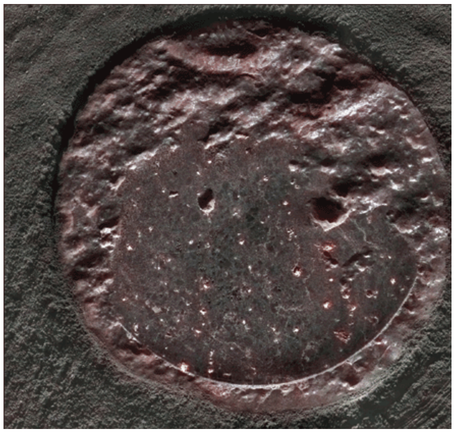


Figure 6-9. A dust free, cleaned and smoothed surface provides a better target for instrument measurements than an "as-is" surface*.* *Abraded/ground surface on the rock Humphrey at the Spirit site. The ground surface shows no obvious artifacts related to the grinding operation, providing a clear view of the textural details of the rock and a work surface suitable for interrogation by compositional instruments. Brushed and abraded circle is 45 mm diameter. Grayscale image from the MI camera, merged with color from Pancam imager. Credit to JPL/NASA/MSSS.*

The effect of surface roughness on Raman spectra depends on (1) average Raman sampling depth (optical design); (2) optical properties of different minerals (color and Raman cross section); (3) mineral proportions in a rock/soil (a major or minor phases); and (4) grain size with respect to the Raman laser spot size. For a rough (or tilted) rock surface or very fine grained particulate material, the impact on Raman data would be an increase in background, reduction (in %) of "informative" spectra (i.e. the spectra with Raman peaks) and non-detection of minor or trace phases.

The FTIR diffuse reflectance instrument considered for this assessment uses an auto-focus mechanism to optimize the returned signal over a 1 mm x 1 mm spot size, then scans along a 1 cm x 1 cm grid to obtain 100 points. By sampling multiple points and using auto-focus, some surface relief can be tolerated.

Two other instruments were considered: the Micro-XRF and MMI. From the standpoint of tolerance to topographic relief, both of these instruments are relatively robust, tolerating at least +/- 2mm. Micro XRF can do individual point measurements on an unprepared rock surface (or borehole wall). For Micro-XRF scanning modes, a flat surface with topographic relief not exceeding approx. +/-2mm is desired. MMI can acquire data on an unprepared surface, though +/- 2mm is desired to avoid the need for Z-stacking.

6.5.1.4 Surface Preparation: As-flown Capabilities vs. Mars 2020 Demands

To date, two different surface preparation tools have been flown on previous missions: the MER RAT and the MSL Dust Removal Tool (DRT). Both provide dust and loose particle removal via brushing, although there is some concern that the design of the DRT leads to visible scratches in soft rocks and less effective dust removal, as shown on the rock targets known as Ekwir and Wernecke in Gale crater. Only the RAT provides removal of rock material, via a rotary grinding mechanism. As shown by the many tens of brushing and grinding operations by the RAT, the depth, diameter, cleanliness, and smoothness of the resulting prepared rock surfaces are entirely satisfactory for the demands of the measurements planned for the 2020 mission. A comparable capability would thus be sufficient and is considered a threshold requirement.

Given the importance of surface preparation and subsequent measurements to the process of selecting samples for coring and caching, and documenting their geologic context, the surface preparation capability must be available for at least as many samples as planned to be cached. Ideally, such capability would extend well beyond that minimum number of operations both to enhance the characterization of sample context and allow for *in situ* science after sample caching is completed. A brush and grind operational lifetime twice that required for coring and caching is desired.

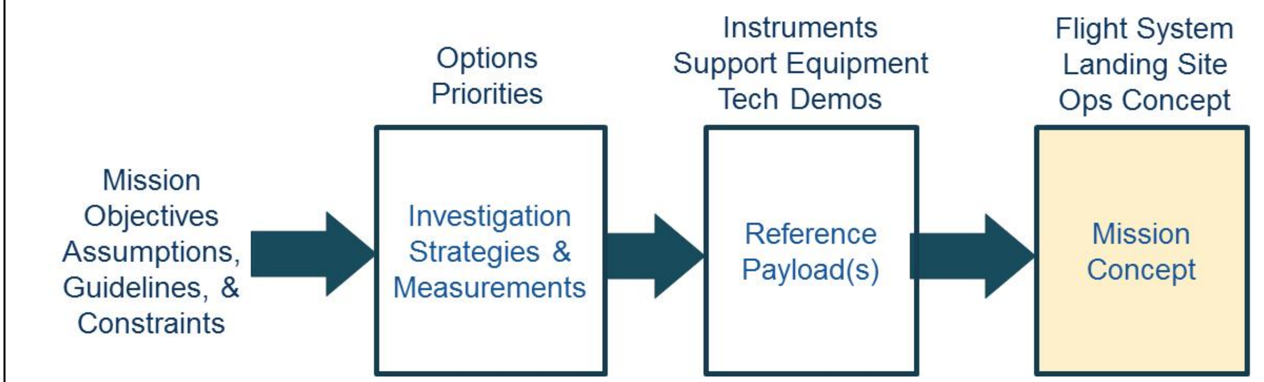
Finding 6-18: The rock surface preparation capability for Mars 2020 should have as a threshold, dust and rock-material removal capability comparable to the MER RAT, with operational lifetime sufficient to match the total number of planned rock sample coring operations. The baseline dust and rock-material removal lifetime capability is 2x the threshold requirement.

6.6 Additional Subsystems

There is a range of additional subsystems beyond those related to sampling and caching that must be addressed for the 2020 mission. The SDT determined that among these, the one with the greatest impact to science concerns the capability to prepare surfaces of rocks for interrogation by the rover's science instruments (Table 6-7).

Table 6-7. Attributes of the other science support equipment left for the Mars 2020 project to establish.

Attributes of Additional Subsystems				
Parameter	Historical		SDT	
	Baseline	Threshold	Baseline	Threshold
SCIENCE ATTENTION LOW PRIORITY AT THIS TIME				
Arm - stability	Defer to project to evaluate			
Arm - positioning accuracy	Defer to project to evaluate			
Arm - turret positioning accuracy	Defer to project to evaluate			
Calibration targets	Defer to project to evaluate			
Mast - stability	Defer to project to evaluate			
Mast - positioning accuracy	Defer to project to evaluate			
Landing systems - ellipse size	Defer to Landing Site Sub-team			
Landing systems - hazard tolerance	Defer to Landing Site Sub-team			
Traverse distance in prime mission (traverse rate)	Defer to Landing Site Sub-team			
Autonomy --??? Ability to navigate, take pics/measurements?	Defer to project to evaluate			
Observation Tray (e.g., observe core/regolith sample w/ instruments)	NO	Defer to project to evaluate		
Organic -Free Blank	YES	Defer to project to evaluate		
Planetary Protection	Defer to PP			
NOTE: The following are MSR-related requirements NOT assumed to be the responsibility of Mars-				
Collect sample of martian atmosphere				
Whole-cache Encapsulation Specs				
maximum shock on Earth re-entry that may affect sample mechanical integrity				
Cache time on surface (maintain scientific integrity)	3350 sols (DS, JSWG)			



Current location in the "Roadmap"

7 Operations Concept and Strategies

7.1 Introduction

While the proposed Mars 2020 rover mission would include a sample caching effort (Science Objective C), this would not be its sole function. The activities that lead to identification of which geologic materials to collect and cache would also be necessary to establish the geologic context and history of the site (Objective A), assess the evidence of geologic records of past, habitable environments (Objective A), and seek biosignatures or rock materials with biosignature preservation potential (Objective B). During this time, the rover would also conduct investigations to address Strategic Knowledge Gaps (SKGs) for future human exploration of Mars (Objective D).

<u>The Mars 2020 rover would…</u>

…need to carefully balance time spent driving, examining a site, and collecting samples to ensure scientific productivity and a full, returnable sample cache.

7.2 Primary Mission and Sample Caching

The proposed Mars 2020 rover primary mission duration would be one Mars year, 669 martian days or "sols." The duration of a martian day, or sol, is approximately 24.36 hours. The Primary Mission would begin with landing on Sol 0 and continue through Sol 669. The majority of the 669 sols would be spent with the science operations team using the rover to drive to areas of geologic interest; perform the fieldwork and operations necessary to address Objectives A, B, and D; and core and cache samples to address Objective C. This Mars year would also include time spent performing hardware commissioning activities, flight software updates, a Solar Conjunction period (occurring approximately every 26 months) in which communication with Earth is interrupted, and anomaly resolution.

The threshold Mars 2020 sample caching capacity is 31 samples (Finding 6-3) with a baseline capability that would allow for the collection of up to 25% more than this (Finding 6-4). The 31-sample capacity is derived from consideration of sample diversity, mass, and packing volume (Section 6.2.3.1). Two to three of the 31 samples would be used as blanks and standards (Section 6.2.4.5).

Thus, a goal for Mars 2020 would be to fill the cache—28 samples plus 3 blanks/standards—within the duration of the one Mars year primary mission. Success in attaining this goal would be dependent on many variables, particularly the nature of the landing site, the amount of time spent driving versus studying the geology of the site and identifying materials to core and cache, plus the specifics of science instrument operating efficiency on the martian surface and the overall design of the operations effort).

Finding 7-1: Filling the 31-sample cache with 28 scientifically meritorious cores and 3 blanks/standards within one Mars year would be a *goal*, not a requirement.

7.3 Regions of Interest

The nature of the Mars 2020 landing site—and where the rover lands relative to the geologic features of highest scientific priority—is a critical, and presently unknown, variable that heavily influences the outcome of achieving the goal to collect 28 samples in one Mars year.

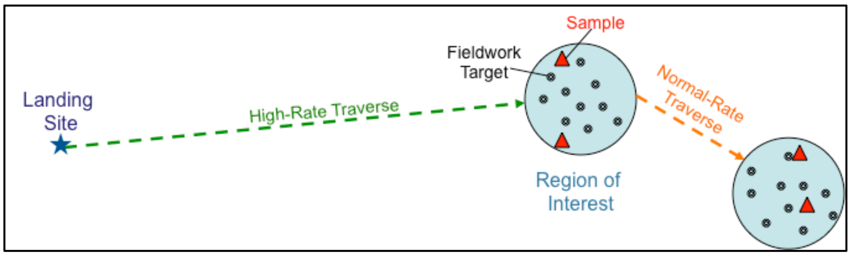


Figure 7-1. Multiple samples would likely be acquired at any given "region of interest". *Representation of spatial relationships among landing sites, regions of interest (ROIs), and specific sampling locations. ROIs could be identified from orbital images to contain minerals or rock structures that might have permitted and preserved biosignatures. Within an ROI, rover-based sensing would enable identification of candidate rocks, and detailed study of those would yield coring/caching possibilities. Examples of ROI would be Home Plate for the MER Spirit rover, and the Yellowknife Bay area for the rover Curiosity*

A key concept for modeling operation strategies for the proposed Mars 2020 mission is that of Regions of Interest (ROI). These are defined as the areas on Mars in which the science team would spend time using the rover and its tools and instruments to characterize the geology, perform detailed investigations of selected materials, interrogate materials for suitability for coring, and collect and cache perhaps multiple samples. Examples of ROIs from previous rover missions include Endurance crater (Opportunity site), Home Plate (Spirit site), and Yellowknife Bay (Curiosity site). Fig. 7-1 illustrates the ROI concept. The most important ROIs could and should be identified and prioritized before the rover would land. The highest-priority ROI, then, becomes the pace setter for the one Mars year mission.

7.4 Surface Operations Activities and Time Consumption

Necessarily, surface operations involves making decisions about how much time would be spent driving, how much time would be spent conducting fieldwork, and how much time would be spent collecting and caching samples (Fig. 7-2). How much driving might be required would depend greatly on where the rover has landed and where the highest-priority ROI is located. Decisions about the time spent on each of these activities would be governed by the strategic science objectives—for example, drive X km to reach a specific region of interest; perform Y observations to characterize a given trait of the region of interest; and also by how much time it would take to accomplish the specified objective (how much time to traverse X km, how much time to perform Y observations, etc.).

7.4.1 Time Spent Driving

Time spent driving is a function of distance and speed. The total distance the rover would need to drive is heavily dependent on where the rover touches down on Sol 0, and where it needs to be driven so as to provide the science team access to the highest-priority geologic outcrops and materials. The "speed," in terms of distance traversed per sol, depends highly on the physical characteristics of the surfaces (e.g., slopes, regolith conditions) over which it would traverse. (For the purposes of this discussion, we ignore driving required to approach individual targets once inside a region containing high-priority geologic materials; those drives are considered part of the "fieldwork" activity.) The time spent driving on average, then, is roughly total distance divided by average "speed" expressed as average distance traversed per sol, excluding target approaches (Fig. 7-3).

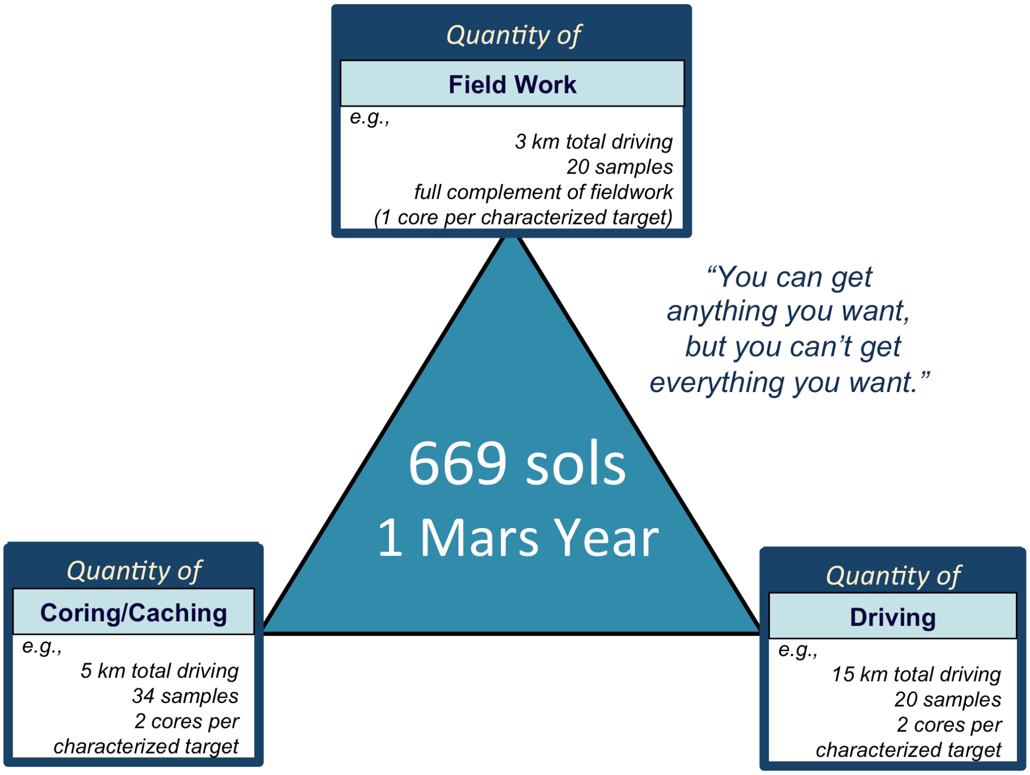


Figure 7-2. It is not possible to maximize the quantity of coring/caching, drive as much as possible, and conduct exhaustive context geologic studies*. Example trade-offs resulting from modeling how the 2020 rover would spend its one Mars year primary mission.*

7.4.2 Time Spent Conducting Fieldwork

Fieldwork is a term used here to encompass all of the effort expended to characterize the geology, assess habitability and preservation potential, identify possible biosignatures, and prepare any potential cores for caching. In particular for the Mars 2020 mission, fieldwork would include acquisition and analysis of contextual imaging and mineralogy measurements, targeted contextual and fine-scale imaging and mineralogy observations, close-up elemental and organic detection measurements, and, as needed, preparation of rock surfaces by brushing and/or abrasion. Fieldwork also would include the conduct of experiments in support of human exploration. Fieldwork measurements would set the stage for selection of what to core, and which cores to cache for possible return to Earth; this effort would include the engineering interrogation of materials for their suitability to be cored.

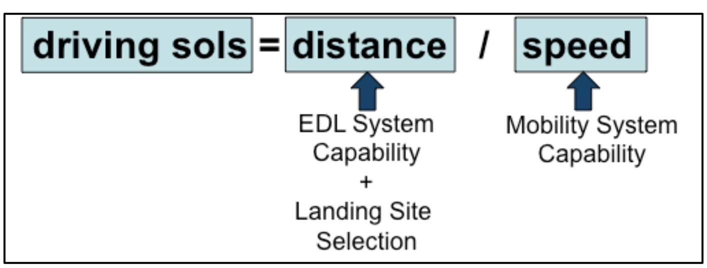


Figure 7-3. A rover could spend less time driving if it lands closer to the areas of high scientific interest*. Rover arrival at high-priority geologic materials (Fig. 7-1) depends on where the rover lands, how close the rover lands relative to the highest priority materials, and how long it takes to drive from the touchdown location to the priority geologic materials).*

7.4.3 Time Spent Coring/Caching

Compared with time spent driving and conducting fieldwork, the time spent coring and caching would be relatively incompressible, and only represents a small fraction of the total available mission operations duration. Given previous robotic operations experience (e.g., MER RAT and Curiosity drilling), we assume that, at a minimum, only one sol is consumed per coring and caching event. That is, to fill a sample cache capable of holding 31 samples (including at least 2 blanks) requires a minimum of 31 sols of the 669-sol mission. This one sol per coring and caching event implies that the core is extracted, encapsulated, and placed in the cache on a single sol with no ground-in-the-loop, decisional steps; this is consistent with present engineering knowledge of how the coring/caching system for Mars 2020 operates. If additional cores could be acquired for on-site analysis or anomaly resolution, or if the cache were capable of holding more than 31 samples, or cached samples could be ejected and replaced, then additional time would be required for coring and caching.

7.5 Overview of Operations Concept and Point Design

Figure 7-4 shows a point design that gives an overview of the 2020 rover operations concept. The numbers of sols shown for each activity is just one example or one permutation of the modeling (described in the next section and in Appendix 8) that was performed to support this study. This figure is not intended to imply that all driving would be completed before fieldwork begins, for example, but rather to show the relative numbers of sols for each activity type for this particular point design, and the breakdown of what would be involved in the operations concept for the fieldwork activity. The particular point design depicted here—comprising distance traversed, amount of fieldwork, and number of samples—is merely one point in the trade-space triangle shown in Figure 7-2. As noted above, a critical variable is the total traverse distance needed to meet the science objectives due to the characteristics of the landing site, where the rover would land, and how far the rover would have to drive to reach the highest priority ROIs.

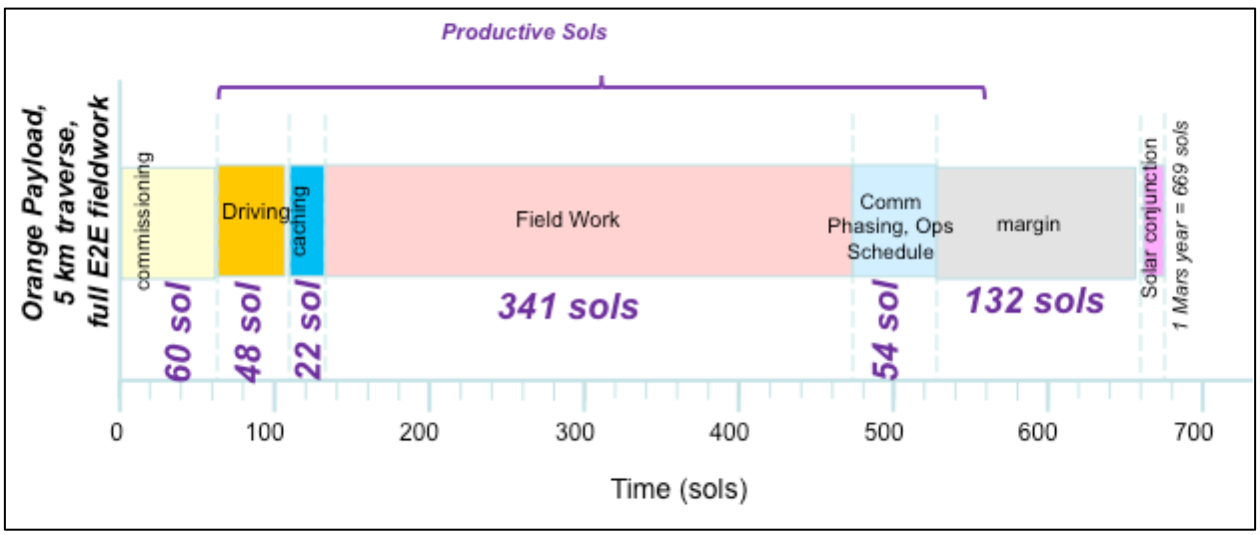


Figure 7-4, Example/Point Design in which most of the primary mission duration would be spent investigating the geology of the field site. *This figure illustrates one example in the population of scenarios represented by the trade-space described in Figure 7-2. This example shows a 5 km drive, 22 cores collected and cached, and the full complement of fieldwork using the Orange strawman payload (as shown in Table 5-3. Additional examples are presented in Appendix 8.*

7.6 Operations Concept Modeling

Appendix 8 describes the details of the operations concept modeling performed for this study, including the assumptions that went into the model. The effort was designed to determine whether the mission concept described herein would be capable of conducting the necessary fieldwork and characterization for habitability and biosignature preservation as well as to produce a cache of up to 31 samples (including 2–3 blanks) in the course of a single Mars year. This assessment assumes that the cache does not have to be located at a specific position on Mars at the end of the primary mission, consistent with the engineering consideration that the cache would need to be extractable from a non-functional rover were it to fail prior to depositing the cache. This assumption means that the entire period would be available for driving, fieldwork, and coring/caching (plus time set aside for rover hardware and instrument commissioning, anomaly resolution, etc.) and that no time would be spent driving the cache to a drop-off point or a final rover "parking spot".

The SDT considered the wide range of potential landing site candidates encompassed—in terms of elevation, latitude, EDL terrain hazards, and ability to traverse across the terrain—by the E2E-iSAG Reference Sites (E2E-iSAG, 2012), the final four MSL candidate sites (Golombek et al. 2012), other sites proposed for MSL (Grant et al. 2011), and additional sites suggested in recent years for missions launching in 2018 and beyond (Grant et al. 2012). These sites are further identified in Appendix 6 and discussed in Section 8. In particular, the SDT paid close attention to the E2E-iSAG (2012) Reference Sites, except the one outside the 2020 rover latitude range (Ismenius Cavus), and the ROIs and traverse distances between the ROIs at these sites determined by JSWG (2012). For each of the E2E-iSAG Reference Sites, the JSWG (2012) found that, assuming an MSL-like landing ellipse size (20 x 20 km), traverse distances could potentially be between 10–25 km, and in some cases, several tens of kilometers more.

In a generalized, modeling sense, time spent driving would be time not spent conducting detailed fieldwork nor coring and caching. Conceptually, driving is in tension with fieldwork, as the time spent coring/caching is both relatively small and incompressible (Fig. 7-3). Our modeling found that missions involving more than 10 km of driving (over traversable surfaces with an average traverse rate of 100 m per sol) are challenged to collect more than 20 samples (plus 2 blanks) in one Mars year unless the quantity of fieldwork is reduced considerably. Example methods to reduce the time for field work include (1) performing fewer rock abrasions and brushings—and associated subsurface observations—per sample cached, or (2) extract two (or more) cached cores from a single characterized target, such as on either side of a geological contact or a vein and its host rock.

Finding 7-2: With the proposed mission concept, the charter-specified objectives for Mars 2020 can be achieved at a variety of landing sites.

7.7 Strategies for Improving Overall Productivity

Although plausible mission scenarios can be found for a variety of landing sites within the trade-space between sols spent driving, doing fieldwork, and caching; and, given the current set of assumptions (Appendix 8), there are cases for which the 2020 project would be challenged to meet the goal of filling the cache with scientifically valuable samples within a Mars year.

Finding 7-3: To ensure that the most scientifically valuable returnable cache would be achieved, priority should be given to developing the payload and spacecraft systems with consideration for increasing both the number of sols dedicated to advancing science objectives and the productivity during those sols.

To reduce the amount of time needed for the driving and fieldwork portions of the trade-space—and therefore to widen the pool of possible landing sites, increase the amount of fieldwork that could be done, and/or increase the number of samples that could be cored and cached within the 1 Mars year mission—we offer suggestions to NASA, the Mars 2020 project, and the Mars 2020 science team regarding the following: Landing site selection, science instrument selection, project development and science team. These suggested strategies are all about increasing the number of well-characterized, diverse samples in a scientifically returnable cache.

7.7.1 Landing Site Selection

Landing site selection would play a *major* role in ensuring operations productivity. Of critical importance would be to seek reductions in time spent driving to reach the highest priority geologic materials. Of similar importance would be to seek attributes of a landing site that reduce the amount of time needed to conduct fieldwork (e.g., dusty surfaces obscure geology, increasing the amount of time needed for fieldwork). The most promising options include (not prioritized):

- Emphasize selection of a site that presents the desired geologic diversity (e.g., E2E-iSAG (2012) prioritizations) in as small, compact, and navigable area as possible.
- Before landing, perform detailed geologic mapping of the site and use this to prioritize the places (ROIs) the rover would go to investigate geology, seek biosignatures, and collect and cache samples.
- To reduce the time spent driving, plan to land as close as possible to the highest priority geologic materials (highest priority ROI). This might require a landing ellipse size smaller than the as-flown MSL design.
- If lower-priority materials (lower-priority ROIs) would be encountered first along the traverse from the touchdown point (landing spot) to the highest priority materials, use the prioritization of the ROIs to set the pace at which, and order in which, those lower-priority ROIs are investigated.
- Landing in an overly dusty region that obscures the underlying mineralogy from context and fine-scale measurement would decrease utility of orbital observations and increase difficulty in understanding the geological context of the field site. Brushing rocks to remove dust would also add time, slowing the pace of fieldwork progress.

Regarding dust-free surfaces, an example of a thin coating of dust is the case encountered by Curiosity at the Yellowknife Bay ROI. There, the fine-grained, gray rocks both brushed and drilled during the January–May 2013 period had a thin coating of reddish dust. Examples of relatively dust-free Mars bedrock outcrops are those of the light-toned, sulfate-bearing sandstones investigated by Opportunity on Meridiani Planum (e.g., Squyres et al 2006). Surface mineralogical detection in orbiter observations (e.g., multispectral visible, near-infrared, thermal-infrared data) is a good indicator of a dust-free surface. Orbiter observations indicated that the rocks investigated by Curiosity at Yellowknife Bay are coated with dust but also indicate that the strata on the lower northwest slopes of Aeolis Mons (also known as Mt. Sharp) are sufficiently clean of dust that mineralogical detections from rocks have been made (Milliken et al. 2010; Seelos et al. 2013).

Finding 7-4: Choice of landing site and prioritization of regions of interest within that site would play a *major* role in ensuring operations productivity and full acquisition of cached samples within the constraints of a one Mars year Primary Mission.

For Mars 2020, the landing site selection process (see Section 8) would define trades between the likely number of samples to be collected and cached, the distance needed to traverse to access them, and the potential value of the samples relative to mission objectives. For example, at one site, the possibility of a shorter traverse could provide the potential to collect 20–28 samples. By contrast, another site might offer access to samples of perceived higher science value, but might require a longer traverse to access those samples. The result might be that less than 20–28 samples would be cached during the primary mission, but collection of a cache deemed of higher science value than the first site.

7.7.2 Science Instrument Selection

To improve the rate at which fieldwork progresses, NASA should consider selecting science instruments that reduce the number of sols spent acquiring data, reduce the frequency of ground-in-the-loop decision points, and reduce operational complexity. Prospective options, not listed in prioritized order, include:

- Consider selecting science instruments that could acquire data quickly and that have the ability to acquire a greater number of measurements per sol.
- Consider selecting science instruments that have low operational complexity. Some examples include: instruments that are amenable to commanding via re-usable command sequences, instruments that do not impose complex or precise pointing/placement constraints, and instruments that have the ability to keep themselves safe without operator intervention.
- Consider selecting science instruments that could rapidly acquire (and process onboard, if necessary) decisional data before the scheduled downlink period.
- Consider selecting instruments that minimize power consumption, including power for heating the instrument to operational temperature. Reduction in heating duration could permit more science measurements to be acquired on a given sol.

Instruments capable of rapid decisional data acquisition should be encouraged. Instruments requiring multi-sol operations to generate decisional data would significantly increase the time required for fieldwork and decrease the time available for other activities. Instrumentation that needs low light levels for optimal performance, thereby generating decisional data late in the command cycle timeline, would increase fieldwork duration. Instruments with onboard autonomy might allow detailed target choice without ground-in-the-loop and could reduce fieldwork duration. Reduction in the need for ground-in-the-loop decisions needed for contact tool or instrument placement, mast or mobility pointing of instruments, etc., would be valuable.

7.7.3 Project Development

To improve the overall rate at which the 2020 rover team could identify which samples to collect, core, and cache, our key proposals, not listed in prioritized order, for the project are:

- Reduce the size of the landing ellipse, relative to the MSL as-flown capability, so that the rover could land as close as possible to the highest priority ROI.
- Improve the traverse distance achievable per sol on drive sols relative to the present MSL capability. Example suggestions include improving autonavigation speed and increasing so-called “blind drive” distances with improvements to navigation imaging. Improvement to navigation imaging could be implemented in the rover’s navigation cameras and/or the NASA Science Instrument AO could encourage (and describe requirements for) science camera augmentation to the navigation capability.
- Reduce the complexity of operating the robotic arm, sampling, and caching system relative to the MSL robotic arm and Sample Acquisition/Sample Processing and Handling System (SA/SPaH). (Anderson et al. 2012b).
- Reduce power consumption related to and duration necessary for actuator heating so as to provide more power and time on a given sol to collect science data, use the rover’s tools, or drive.
- Complete the validation and verification (V&V) tests for critical science activities, including coring and caching, before landing.
- Minimize current threats to MSL-like communications (e.g., availability and timing of overflights of relay orbiters in 2021–2023 and beyond). Ensure at least MSL-Primary-Mission-like downlink data volume capacity. Some possible solutions include (1) MRO-like data volume Direct to Earth downlink from the rover and (2) put in place a new orbiter, in an orbit designed specifically to relay data from assets on the ground, in place before the 2021 rover landing.
- Consider seven days per week tactical operations, with sufficient staffing and science team size, throughout the primary mission. Avoid holiday stand-downs. Avoid hibernation periods (as might be necessary for a solar-powered rover).
- Consider minimizing the impact of Solar Conjunction. Minimize sols unavailable for science measurement owing to preparation for Solar Conjunction. Consider performing autonomous science investigation activities during Solar Conjunction that reduce the schedule impact of those activities on sols spent doing fieldwork, driving, and sample caching outside of this period.

- Ensure sufficient resources for the Mars 2020 science team, as well as the project, to participate in daily tactical and strategic planning and operations more fully than on previous missions.
- Consider performing routine night operations. Mindful of power, thermal, and decisional downlink constraints, consider whether sols spent driving or doing fieldwork can be compressed by acquiring measurements both day and night.
- Consider reducing the impact of Earth/Mars operations and communications phasing; reduce the number of “restricted sols” which can slow the progress of a surface rover mission.
- Consider having 2–3 operations centers (e.g., located in the same time zones as the 3 Deep Space Network, DSN, stations) and use these to keep operations synched with communications and Mars surface operation schedules.
- Consider providing flexible timing of decisional downlink to fit both planned activities on Mars that acquire the decisional data and the ground operations schedule (Earth–Mars time phasing).
- Reduce planning and sequencing complexity. Consider, for example, having instruments, tools, and capabilities that offer fewer options, fewer “knobs and dials” for the science team to select so as to speed sequence preparation, checking, approval, etc.

- Reduce the dependency on ground-in-the-loop, particularly for robotic activities by considering a) investment in advancing autonomy (such as enabling safe/trusted multi-sol driving sans ground-in-the-loop, enabling autonomous arm end effector placement), and b) sufficient testing to engender confidence in the technology.

7.7.4 Science Team

Science team size, structure, and efficiency of planning for operations would also be vital to ensuring that the sampling and caching activities could be achieved in a single Mars year. A decision to cache a particular sample is a significant decision, given the expense of spaceflight missions and the effort that would be expended to retrieve these samples. Our key proposals, not listed in prioritized order, are:

- Seek ways to streamline, relative to MSL and MER experience, the team’s decision-making process on where to drive, what to do in a given ROI, what data to acquire that lead to the decision to core and cache a sample.
- Provide sufficient resources to the Mars 2020 science team during mission development (pre-launch and during interplanetary cruise) to devote effort to studying data that inform the team of the nature of the geology of the final, selected landing site.
- Consider having a Participating Scientist program and adding them (not just selection, funding in place, too) to the team early enough to contribute to the analysis of the selected landing site and prioritization of its ROIs.
- Consider providing sufficient resources so that the science team and participating scientists should begin detailed study of the landing site as soon as the final selected site is known.
- Consider, at every step through the course of the landed mission, the first order scientific priorities. Focusing on tactical decision-making should narrow the scope of science discussions to enable rapid decisions on what to collect and cache.

> **Major Finding 7-5:** Multiple strategies to improve on the modeled, reference operations scenarios will be available as the proposed mission is further developed.

7.8 Filling the Cache

The Mars 2020 rover would have the capacity to cache a minimum of 31 samples, two to three of which would be blanks or standards. The remaining 28 samples would be extracted from martian rock and regolith.

As noted above, the *goal* would be to acquire the 28 samples within the Mars 2020 Primary Mission duration of 669 Sols (Section 7.2). The goal of filling the cache is coupled with the goal of acquiring a scientifically returnable cache (Section 3.4)—that is, including samples of scientific merit. There is no point in arbitrarily filling the cache simply to meet the goal of 31 cached samples in a year.

The SDT's operations concept modeling shows that there are ways to collect 28 samples in one Mars year. There are also many ways in which the number of samples acquired might come up short of 28, particularly if considerable time is spent driving to the highest priority ROI.

The SDT believes that no requirement should be imposed regarding the number of samples to be cached within one Mars year (Finding 7-1). The design of the Mars 2020 mission should be focused on ensuring that the science team has the capability to fill the cache with scientifically returnable materials within 1 Mars year. However, the specific number of samples actually cached during that period should be a matter for the Mars 2020 science team, its Project Science Group (PSG), in consultation with NASA, to evaluate and decide based on the final selection of a landing site, the specific location of the rover post-EDL, and the geology encountered during the mission.

7.9 The Importance of a Potential Extended Mission to the Science of Mars Sample Return

For the samples in the proposed Mars 2020 cache to be transported back to Earth, there would need to be a successor surface mission that would include the capability to retrieve the cache (probably using a so-called "fetch" rover) and to transfer it into a Mars Ascent Vehicle. The planning for that successor mission is in its infancy. However, given that the Mars 2020 rover might become disabled with the cache still on board, it is assumed that the "fetch" mission would have the capability to recover the cache from a disabled Mars 2020 rover. The end-state of the cache, whether remaining on the rover or being placed on the ground, is still under consideration. These are issues that need further discussion within the Mars 2020 project and with NASA.

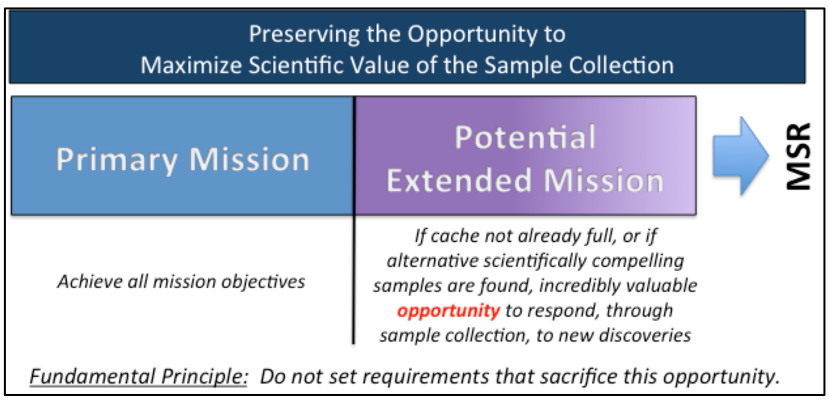


Figure 7-5. The science return of the Mars 2020 mission is enhanced by preserving the opportunity to conduct an Extended Mission in which the Science Team can continue both the rover's field science and sample collecting and caching activities

7.9.1 Enhanced Science Opportunity

If the cache were to stay on the rover, and the rover should remain functional at the end of the Primary Mission, then there would be an extremely valuable opportunity to maximize the science of Mars Sample Return by having the Mars 2020 rover continue both its exploration and its sampling campaign (see Fig. 7-5).

There are two primary reasons:

- The cache might be under-filled at the end of the Primary Mission, especially if a landing site were chosen where the scientific targets might be spread out so that extended driving would be necessary.

- Even if the cache were full, as the rover makes additional discoveries in its hoped-for Extended Mission, it might encounter new kinds of samples that would significantly improve the scientific yield of the sample suites already in the cache.

Consider, for example, the multiple-extended mission of the Mars Exploration Rover, Opportunity. On its 2681st sol, it reached Endeavour crater. That is *four* Mars years into its mission, around the start of its fourth Extended Mission. The geologic materials encountered at Endeavour were unlike any rock previously examined by Opportunity; instead of sulfate-bearing aeolian sandstones, the team began to find, among other things, basaltic breccias, hydrothermal alteration products, and gypsum-rich veins (Squyres et al. 2012). If Opportunity were a sample-caching rover with a capacity to store 28 cores, it seems likely that its cache would have been filled during the preceding 4 Mars years. At this point, if the team had the capability to remove and replace samples, they would likely have done so. The geological diversity and the potential for increased probability of sampling past, habitable environments and perhaps biosignatures increased as the missions was further and further extended.

As a result, the SDT believes the ideal Mars 2020 mission, too, would be able to continue to encounter new geology and cache new samples, well beyond the end of the Primary Mission (assuming the hardware is functional and the resources could be made available by NASA). In order to protect the Extended Mission opportunity described above, the SDT proposes that the Mars 2020 project deliberately avoid requirements that would interfere with this opportunity.

Major Finding 7-6: Based on important discoveries made during previous rover extended missions, the ability to continue to collect and cache samples during an extended Mars 2020 rover mission must be protected through proper design of both the 2020 mission and the architecture of Mars sample return.

7.9.2 Sample Replacement

With regard to upgrading the sample collection over time, E2E-iSAG (2012) pointed out the value, from a decisional perspective, of having the ability to replace at least 25% of the samples in a cache (see Section 6.2.3.2). This reflects the practicalities of geological fieldwork, in which it is necessary to make sampling decisions on the rocks immediately available before knowing what types of rocks exist in the yet unexplored terrain. For a 31-sample cache, assuming three of the slots are reserved for blanks and standards, this implies the ability to replace at least seven samples.

Replacing a sample already in the cache would be a challenging engineering task. One simple implementation is to increase the sampling capacity to 37 slots, which the SDT views as one version of a baseline solution (Finding 6-4), and allow the samples that might have been replaced to remain in the cache as extra, lower value samples. A better solution for science, which the SDT considers to be an alternate baseline, would be to have the ability to extract samples from a 31-slot cache, and to replace them with more preferable samples. This would allow for the option to replace more than seven samples, which would have arguably far greater value to MSR the longer the Mars 2020 mission would be operational. Using a larger 37-slot cache may have implications for additional mass and volume for the potential future retrieval and transportation missions of MSR. These potential implications will need to be addressed by both the 2020 project office and the Mars Program Office. If these implications drive resources unnecessarily, the SDT deemed a mission without sample replacement capabilities as scientifically worth flying (i.e. this is the threshold position).

7.10 Implications

Using the model described in Appendix 8, plausible mission operations scenarios that suit a variety of possible landing sites could be found throughout the ternary that describes the trade-space between time spent driving, time spent conducting fieldwork, and time spent coring and caching samples (Fig. 7-2). The key strategic implications of the operations scenario analysis are:

1. Landing site selection must take into account the trades between drive distance and geological complexity of the site in order to reach the goal of filling a 31-slot cache within 1 Mars year.
2. At some landing sites, acquisition of 20–28 scientifically selected samples in 1 Mars year would take concentrated effort. The appropriate number of samples, of high scientific merit, to be collected is a matter for the Mars 2020 science team, its PSG, and their discussions with NASA, to determine. The SDT believes full determination depends on the site selected, where the rover lands on Sol 0, and the accessible geology encountered during the Primary Mission.
3. The potential to identify, collect, and cache samples during an Extended Mission is an extremely valuable strategic opportunity, and should not be precluded. The MER extended missions illustrate the potential for accessing new and scientifically valuable materials well after the end of a rover's first Mars year.
4. Optimizing surface operations performance requires attention by NASA as early as the science instrument Announcement of Opportunity (AO); the selection of instruments that support efficient use of resources and have fewer operational constraints could facilitate improvements in the reference operations scenarios.
5. The Mars 2020 project should pursue opportunities that reduce landing ellipse size, increase mobility traverse rates, and improve operability and communications relative to MSL to improve non-payload aspects of the reference operations scenarios.
6. The Mars 2020 science team should be looking at the final, selected landing site as early as possible to identify and prioritize ROIs. If NASA intends for this project to have participating scientists, they should be added early enough (at or before landing site final selection) to participate in this effort.
7. The project and science team should seek ways to streamline, relative to previous mission experience the scientific decision-making process during the surface mission; focus on the highest priority objectives and caching of the highest priority geologic materials.

8 Landing Site Access Considerations

8.1 Introduction

Site selection is central to the success of the 2020 mission. The Mars 2020 rover must be able to access the highest-priority geologic materials that allow the science team to address Objectives A, B, <u>and</u> C, as well as facilitate Objective D investigations. Before final selection, therefore, detailed evidence must be presented which shows (1) that the proposed site has the potential to provide access to a geologic record of past, habitable environments, (2) that biosignatures may be preserved there and (3) that geologic materials of interest for sample caching and eventual return to Earth are present.

> <u>*The Mars 2020 rover project would…*</u>
>
> ***… select improvements in landing technology based on compelling community-proposed locations for access to unprecedented science potential.***

The Mars 2020 SDT charter charged the team to consider aspects of improving access to "high-value science landing sites". In the context of planning for the 2020 mission, a "high-value science landing site" is one at which the objectives of the Mars 2020 mission could be achieved, including that of caching samples for possible return to Earth. In particular, a landing site must have characteristics suitable for addressing these objectives:

- The site must permit access to an astrobiologically relevant ancient environment (Objective A);
- It must preserve, and allow discovery of, information to decipher its geological record, including both processes and history (Objective A), and information relevant to its past habitability and potential to preserve biosignatures (Objective B);
- It must permit investigation of materials that could contain potential biosignatures (Objective B);
- It must permit assembly of a cache of samples that is capable of meeting Mars sample return scientific objectives, taken as those of E2E-iSAG (2012) report (Objective C); and
- It must be consistent with conducting investigations that meet Objective D.

Finding 8-1: Landing/field site selection criteria for Mars 2020 should be driven by objectives of both *in situ* science investigations and returned sample science, and are broadly consistent with the findings of E2E-iSAG (2012).

8.1.1 Site Selection Constraints

Site selection for Mars 2020 is a function of the science objectives as placed within the context of a one Mars year Primary Mission duration and the engineering constraints of the as-flown MSL EDL and Mobility systems modified to the extent that the project's cost and schedule constraints allow.

An important assumption made by the SDT is that the EDL capabilities of follow on missions to retrieve and return the sample cache would be comparable to or better than those available for the 2020 mission. The Mars Sample Return architecture must also be designed such that it permits (or doesn't preclude) the Mars 2020 project to have an extended mission in which the team could continue to collect samples that enhance the science value of the cache. If future mission design related to retrieval of the 2020 cache places significant constraints on the location and terrain where the cache must be left (e.g., for retrieval by a fetch rover vs. one more capable), then the constraints on landing sites that impact access and other aspects of the 2020 mission could be reevaluated and modified as necessary. It is likely that such changes would significantly impact the number of samples collected and cached during the 2020 Primary Mission.

8.1.1.1 Constraints from Mission Objectives

Mars 2020 is both an astrobiology mission and a sample caching mission. A major goal of the landing site selection process would be to identify a site on Mars that satisfies engineering constraints and preserves evidence of astrobiologically relevant ancient environments so that the site could be examined more closely on Mars and samples could be collected for Earth return. The Mars science community's goals for collection of samples intended for return to Earth have been presented in recent reports (e.g., E2E-iSAG 2012; JSWG, 2012; MPPG 2012). Most importantly, Figure 3-19 shows E2E-iSAG's (2012) proposed scientific objectives for sample return (E2E-iSAG, 2012), with the implied types of samples to be returned. In their view, which this SDT adopts, the highest priority samples are those of sub-aqueous sedimentary origin, hydrothermal origin (chemical sediments), and rocks altered by low-temperature or hydrothermal aqueous fluids. These types of samples address the highest scientific priorities relating to past life and habitability, aqueous processes, and climate. E2E-iSAG (2012) found that the second priority type of sample was unaltered igneous rock, acquired from in-place outcrops, which would address high priority objectives involving the geological and cosmological evolution of Mars and provide some temporal context (age dating) for rocks investigated at the sample collection site.

8.1.1.2 Constraints from EDL System

The starting assumption for the SDT, based on NASA direction, was that the Mars 2020 mission would use the successful, as-applied MSL EDL system. The constraints this EDL system imposed on the MSL site selection effort are summarized in Table 8-1 (additional details on constraints can be found in Grant et al. 2011 and Golombek et al. 2012).

Table 8-1. Landing Site Selection Engineering Constraints of the As-Flown MSL EDL System

MSL Landing Site Constraint (see Grant et al. 2010; Golombek et al. 2012)	Summary Parameter Value
EDL landing ellipse dimensions	25 km x 20 km
EDL + thermal + power latitude constraint	30°N to 30°S
EDL landing site elevation	< –1 km relative to Martian datum (effective)
EDL slope/roughness constraints	2–10 km < 2°; 2–5 m < 15°; rocks < 0.55 m
Mobility system capability (go to permitted)	Up to 20 km odometry

Relative to the MSL landing opportunity in 2012, the 2020 opportunity presents more favorable arrival and EDL conditions. For example, entry conditions are benign compared to those that could be accommodated by the MSL design. More importantly, the expected state of the martian atmosphere at the L_s of landing in March 2021 is significantly more favorable than the atmosphere experienced by MSL in August 2012 (Fig. 8-1).

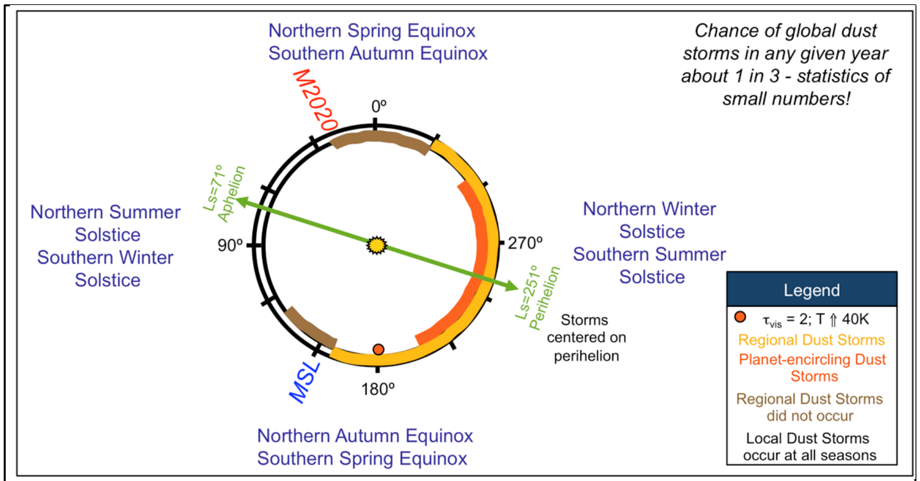


Figure 8-1. The Mars 2020 rover would land at a time of low dust storm activity. *Ls and dust storm behavior during EDL Season for MSL and the proposed Mars 2020 mission.*

For most latitudes, the atmospheric density at EDL for the 2020 opportunity is nearly 15% higher than that experienced by MSL, as shown in Figure 8-2. Atmospheric density, especially in the lower atmosphere, is critical for the performance of EDL systems. More atmospheric density allows the vehicle to slow down more quickly and at higher altitudes. This enables the system to complete the required preparations for landing at higher altitudes and results in increased landing site elevation capability. Whereas the as-flown MSL EDL system was only capable of safe landing at site elevations up to –1 km MOLA in the 2011 launch opportunity, the same system would likely be capable of landing at site elevations up to +0.5 km MOLA in the 2020 opportunity.

Given that the science payload has not yet been selected and there remain some uncertainties regarding overall rover design as well as the relative immaturity of EDL analysis of the 2020 opportunity, site elevation development margin is necessary when considering potential landing sites. A landing site elevation capability of –0.5 km MOLA budgets for 1 km of margin, and would likely account for developmental threats to landing elevation.

The MSL EDL system used a 25 km x 20 km landing ellipse for landing site selection purposes. Landing precision performance without enhanced capability is expected to be unaffected by 2020 opportunity considerations. Note that just as with MSL, landing ellipse size would likely shrink during/after a 2020 landing site selection process, assuming that conservatism in early wind and design assumptions would be retired during development. Finally, the MSL EDL system was capable of reaching sites between 30° S and 30° N. This would not be expected to change for the 2020 opportunity.

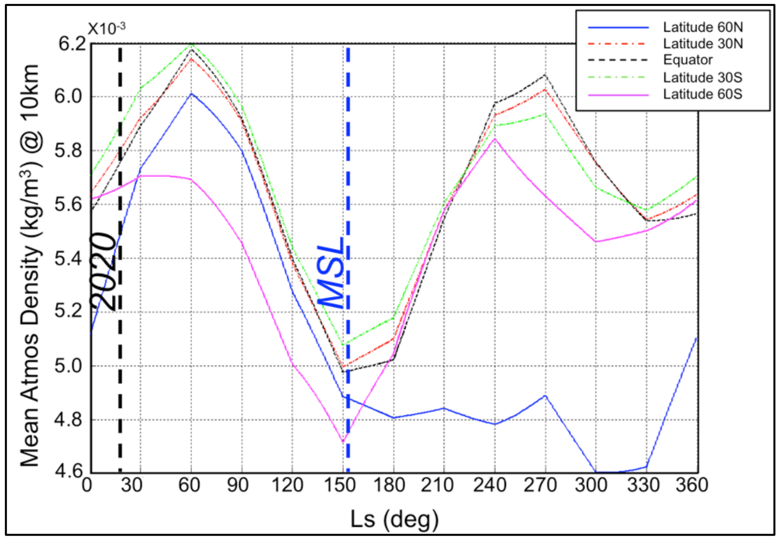


Figure 8-2. Mars 2020 would land when the atmosphere would help slow the rover down during descent*. MSL landed in southern winter, when atmospheric densities were near annual minima. Mars 2020 would land in northern winter, when atmospheric densities are high.*

8.1.1.3 Constraints from Mobility System

For the rover to access geologic materials of relevance to addressing the mission objectives, it must not only be able to land near those materials, it must be able to drive to and interrogate them. The amount of time required to reach the materials of interest, after landing, is a function of where the rover landed and how fast it could be driven to those materials (see discussion in Section 7). Thus, the site must be trafficable. The as-flown MSL Mobility System is capable of driving 20 km in an odometric sense; this requirement was driven by the size of the MSL landing ellipse and the desire to ensure the rover could drive out of this ellipse, at least to some distance, if necessary. Sites with slopes and surfaces similar to those traversed by the MER and MSL rovers are considered to be trafficable for the Mars 2020 Mobility system.

8.2 Mars 2020 Site Selection

8.2.1 Sites of Interest are Challenging to Reach

The Mars science community has been discussing places to address astrobiological and sample return objectives since before there were images and spectra acquired from Mars orbit (e.g., Swan and Sagan 1965). To select an optimum astrobiologically relevant site for study and sample return, trades would need to be made between EDL capability, mobility, mission duration, and science value. Early studies of candidate astrobiology and sample return sites utilized observations largely gathered by the Viking and Mariner 9 orbiters (e.g., Drake et al. 1988; Farmer et al. 1994; 1995). With the enormous volume of data acquired over the past 15 years by Mars Global Surveyor (MGS), Mars Odyssey (ODY), Mars Express (MEX), and the Mars Reconnaissance Orbiter (MRO), the Mars science community has identified dozens of candidate landing sites that might address science objectives regarding Mars habitability, astrobiology, and sample return science (e.g., Grant et al. 2011; Golombek et al. 2012; Grant et al. 2012).

On the Mars 2020 mission, having to drive 5 or 10 or 20 km before reaching the highest priority materials might severely limit the amount of time, during a one Mars year Primary Mission, that is available to select and cache samples (see previous section). However, as was the case for the MSL site in Gale crater, it is possible that the science community and the Mars 2020 science team would decide that the long drive is worthwhile, that the materials, once reached, are the right ones to study, collect, and cache.

The sites of greatest interest tend to be places where dust and regolith are presently not obscuring, or are only minimally obscuring, the view of exposed martian bedrock as visible to orbiting cameras, spectrometers, and imaging spectrometers. In particular, sites of interest are those that have lithological diversity, clear stratigraphic relations (layers, cross-cutting forms, etc.), evidence of aqueous sedimentation and/or hydrothermal activity, and aqueous mineralogy. It is in places with these characteristics that evidence of past habitable environments and biosignatures would most likely be found.

Finding 8-2: Sites of high interest for Mars astrobiological and sample caching studies are those that have little or no dust obscuration such that orbiter observations can be interpreted as presenting a diversity of lithologic materials arranged in a clear stratigraphic context; sites with an interpreted presence of aqueous minerals are of particular interest.

The bedrock characteristics just described are generally identifiable from orbiter observations and tend to be identifiable only in dust- and regolith-free exposures. Areas where little dust accumulates and regolith is stripped away are typically places with steep slopes and/or places where winds are actively removing material. These are places such as impact crater walls, fields of buttes and mesas, the walls of tectonic troughs, and the windblown slopes of some intracrater and intrachasm layered rock outcrops where landing might be impractical. These sites can be difficult to reach with as-flown MSL EDL system landing ellipses, as suggested by the fact that three-quarters of the final candidate sites for MSL were "go-to" sites requiring long drives outside the landing ellipse, and as indicated by the challenges of reaching the majority of the E2E-iSAG (2012) sites with the as-flown MSL EDL system.

Finding 8-3: Relatively dust-free sites of high interest to astrobiological and sample caching studies are most typically found in places with steep slopes and or present-day wind erosion. These sites can be difficult to reach with as-flown MSL EDL system landing capabilities.

8.2.2 Where to Land

Where to land is an extremely important decision that would impact all aspects of the outcome of this mission and the potential scientific return on the investment in sample caching. If previous Mars landed missions are a guide, then the final selection of the landing site would be made by the NASA Associate Administrator of the Science Mission Directorate. In Section 8.4.1, below, this SDT suggests that NASA sponsor a process to solicit Mars science community input and discussion to not only help decide where to land, but in proposing candidate sites whose science merit and physical characteristics could help decide whether enhancements to the Mars 2020 EDL system and/or mobility system are necessary and to help prioritize the Regions of Interest (ROIs) to be visited by the rover at the final, selected site.

Further, because the proposed 2020 mission would cache samples, the community investment in the mission is greater than for prior missions. If the samples are returned to Earth they would become the foundation for a new era of Mars exploration that extends well beyond the 2020 mission lifetime. Hence, the scientific community deserves a stake in proposing the optimal site for the 2020 mission that should become part of the package of information considered in eventual selection of the landing site. As occurred on MER and MSL, the science community proposal would (a) inform the Mars 2020 project regarding which sites to focus attention and resources on to determine whether they meet the engineering constraints for EDL and mobility concerns and (b) inform the Mars 2020 science team and its Project Science Group (PSG) who would ultimately decide which site(s) to propose to the NASA Associate Administrator of the Science Mission Directorate.

8.2.2.1 Back to Gale?

In light of recent press conference and press-release announcements about the MSL science team's observations at the Yellowknife Bay field area in northern Gale crater, the SDT considered whether the Mars 2020 mission should simply be directed to land at the MSL field site in Gale so as to collect and cache materials already identified by the MSL team.

The logic behind this notion is simple. The MSL field site already appears to meet the programmatic goal for astrobiology of a confirmed ancient habitable environment. Returning to Gale has the advantage of building upon an important contextual and chemical knowledge base unique to MSL and its instrument payload. Further, the threshold Mars 2020 mission would use MSL hardware and we already know that the Mars 2020 EDL system could reach Gale and the MSL mobility system could take the new rover anywhere that Curiosity has been.

However, MSL has not yet (as of June 2013) made a discovery in Gale that warrants returning to this site with a subsequent mission. Alternate sites have at least as much potential to achieve Mars 2020 objectives as a return to Gale. By the time the Mars 2020 rover lands, MSL would have already investigated potential habitability of some of the rocks that contain records of paleoenvironments in Gale and, to a modest degree, their biosignature preservation potential. Returning to Gale for Mars 2020 would impose redundant mission objectives for the same rock records. Exploring a new landing site would provide an opportunity to expand our understanding of martian habitability for a different time in its history. Lastly, present knowledge that Gale probably does not meet the baseline landing site criterion for Objective C, from the E2E-iSAG (2012) prioritization, involving access to in-place igneous rocks.

> **Finding 8-4:** Gale crater merits consideration as a candidate Mars 2020 landing site, but thus far, MSL's discoveries do not warrant pre-selection of Gale or other prior landing sites as the Mars 2020 landing site.

Similar arguments could be made for the other finalist candidate landing sites for MSL and for the MER landing sites. In addition, it is important to point out that the objectives of the 2020 mission are distinct from MSL and MER and the criteria used to evaluate the candidate landing sites for those missions differ. In addition, much more data is now available to assess the suitability of different landing site than was available when the Gale site was chosen. Hence, it would be premature to select either the MER or MSL final candidate sites for the 2020 mission.

8.2.3 E2E-iSAG (2012) Reference Sites

Because Mars 2020 would be, in part, a sample caching mission, the SDT considered the E2E-iSAG (2012) Reference Sites, as did JSWG (2012) after it. The E2E-iSAG Reference sites were originally identified to establish a suite of viable candidate sites for sample return assuming the necessity of satisfying threshold science requirements for access to both aqueous sedimentary/hydrothermally altered rocks and unaltered igneous rocks within a known stratigraphic context. Among the many candidate sites that were considered by E2E-iSAG (2012), seven were identified that seemed most likely to allow a mission to meet the E2E-iSAG sample return science objectives and that define a range of initial constraints on landing capabilities for sample return.

All but one of the seven E2E-iSAG (2012) Reference Sites (Table 8-2) has the potential to be a scientifically suitable candidate for the 2020 mission. The Ismenius Cavus site was excluded from further consideration because of its proximity to possible ice-rich mantled terrain (Dehouk et al. 2010). The Ismenius site is viewed as a possible Special Region (SR-SAG, 2006) if interpreted ice deposits exist within the region. Ismenius is also outside the latitude constraints for the Mars 2020 mission by about 3°–4°.

Finding 8-5: Six of the seven E2E-iSAG (2012) reference sites are suitable for consideration for a Mars 2020 landing. The seventh, Ismenius Cavus, is potentially a "special region" or could become an "induced special region" in the event of an off-nominal landing.

The remaining six E2E-iSAG Reference Sites were considered in the context of the as-applied MSL EDL system with the more favorable March 2021 landing conditions. Table 8-2 thus includes entries that describe these sites in terms of how they might stress the as-flown MSL system. Further, the SDT evaluated whether EDL system enhancements of TRN (see Section 3.6.2.2) or THA would improve access to these sites.

Table 8-2. Only one of the 7 E2E landing sites would be accessible with the As-Flown MSL EDL capability.
Evaluation of 6 of 7 E2E-iSAG (2012) Reference Sites for the 2020 Mission

Reference Landing Site	Stressing Parameter	Terrain Relative Navigation (TRN) Needed?	Terminal Hazard Avoidance (THA) Needed?	Notes
Gusev Crater	14.5°S	No, but gives more access to Columbia Hills	No	Operate at 15°S?
Jezero Crater	Rocks	No	Yes	>1% failure without THA
Nili Fossae	-0.6 km elev.	Maybe*	No*	Land up to 0 km elevation, 6% area scarps
Mawrth Vallis 0	Rough	Probably	Maybe	
E Margaritifer	Inescapable Hazards	Yes	Probably Not	>3% ellipse inescapable, 99% success with 300 m divert
NE Syrtis	Scarps	Yes	Maybe	>4% ellipse scarps, 99% success with 300 m divert

*Nili Fossae could become "land on" if TRN and THA are available, but is "go to" if they are not.

Considering the as applied as-flown MSL EDL system, for the 2020 opportunity, four of the six E2E-iSAG (2012) Reference Sites in Table 8-2 are not accessible. The Nili Fossae site was not accessible for MSL's landing in 2012, but with the more favorable atmospheric conditions in March 2021, the Nili site is accessible to the margined elevation constraint described in Table 8-1. The Gusev site is completely accessible without augmented EDL capabilities. The E2E-iSAG (2012) and JSWG (2012) studies assumed the Gusev landing ellipse would place the Columbia Hills, explored by the rover Spirit, at the southeast margin of a 20 x 20 km ellipse but, in fact, including the Columbia Hills *inside* the ellipse would actually be possible for the as-flown MSL EDL system, as this terrain is less rugged than portions of the "final four" MSL candidate site in Eberswalde crater.

Finding 8-6: The MSL landing capabilities as applied are insufficient to access the majority of the E2E-iSAG (2012) reference sites.

8.2.4 Broadening the List of Candidate Sites

The E2E-iSAG Reference Sites were not intended to be a list of the *only* sites on Mars suitable for landing ellipses of the order of 20–25 km and missions that combine habitability, biosignature, and sample caching objectives. However, the E2E-iSAG authors were challenged to identify sites that, on the basis of orbiter data, could be argued to have both of the highest-priority types of materials desired for sample return:

1a. subaqueous or hydrothermal sediments, or
1b. hydrothermally-altered rocks or low-temperature fluid-altered rocks, and
2. unaltered igneous rocks.

Many astrobiologically relevant sites proposed for the MSL mission (Grant et al. 2011) are not E2E-iSAG (2012) Reference Sites but are appropriate to be considered for the Mars 2020 mission and are suited to the range of MSL as-applied EDL and mobility capabilities.

Accessibility of in-place, unaltered igneous rocks is a significant point of difference between the findings of E2E-iSAG (2012) and this SDT report. E2E-iSAG (2012) concluded that to maximize returned sample science, the MSR sample collection would need to include unaltered igneous rocks collected from outcrop. This SDT agrees that these samples are highly desirable, but is concerned about how this would limit, this early in mission development, the number of candidate sites. Further, suppose one of the two on-going rover missions—Curiosity and Opportunity—were to make an important, sample-return-motivating discovery in the coming months or years—but neither site has the unaltered *in situ* igneous rocks; would the Mars 2020 mission be precluded from returning to these sites?

In light of the Mars 2020 emphasis on astrobiology and biosignatures, the SDT judges that the importance of accessing sedimentary and hydrothermal sites outweigh the importance of accessibility to igneous outcrops; however, it is still desirable have access to in-place, unaltered, igneous rocks. Further, the SDT recognizes that relatively unaltered igneous rocks can host several sorts of materials relevant to biosignatures, biosignature preservation, and astrobiology in general, including abiotic organic matter (Steele et al., 2012a, b), data on past environments that may have been habitable (Grotzinger et al 2013), and the possibility that such terrains represent habitable environments on earth (Stevens and McKinley 1995; Chapelle et al 2002) as well as the hypothesized remains of ancient martian microbial communities (McKay et al 1996).

For site selection, one would ideally have many choices of sites where sedimentary, hydrothermal, and unaltered igneous outcrops were present (as in E2E-iSAG, 2012). Of the ~65 proposed MSL landing sites evaluated by E2E-iSAG (2012), only 10 included outcrops of unaltered igneous rock, and only a few of those sites would be accessible using the proposed EDL system for Mars 2020. This may be too few sites to ensure that a suitable final site could be found (based on results of past landing site selection processes). Combining the MSL EDL capabilities and E2E-iSAG site constraints does not ensure that an adequate landing site would be found. There are two options to relieve this impasse: improve the EDL capabilities of Mars 2020 over those of MSL; and/or relax the E2E-iSAG (2012) requirement that the landing site have access to unaltered igneous rocks in outcrop.

Finding 8-7: Access to unaltered igneous rocks as float is considered a threshold-level field site requirement, but requiring that they be collected from known stratigraphic context would add significant science risk to the mission – it may be impossible to access a suitable field site using 'as applied' MSL capabilities.

8.2.4.1 Astrobiologically Relevant Sites

A major, distinguishing characteristic of the choice of a landing site for Mars 2020 comes from the SDT charter, which states that the mission would access an "astrobiologically relevant ancient environment." The SDT interprets this to mean that a site should be sought which has the potential to host biosignatures that, if present, could be accessed by the rover. An "ancient environment" site implies a location where the astrobiologically relevant environment no longer exists, but information about it is inferred to have been preserved in the geologic record.

8.2.4.2 *Stressor Landing Sites*

Review of the landing sites proposed for MSL and to calls for future missions (Appendix 6) reveals that > 60 exist over a range of latitudes and elevations and that possess varied physical properties of roughness, slopes, and "land on" versus "go to" access that can sufficiently seed the site selection process while ensuring sufficient scientific range to favor achieving mission success. It is important to note that the MER investigations in Gusev crater and Meridiani Planum and the MSL investigation in Gale have led to identifications of records of ancient, potentially habitable environments. Hence, the SDT seeks to ensure that these sites are accessible to the Mars 2020 mission and that the ability to access these sites must be preserved until such time that these sites have been considered as candidates and accepted or rejected on scientific grounds.

Finding 8-9: Mars 2020 access to the MER and MSL field sites must be preserved; the threshold mission capabilities must include the ability to return to any one of these three sites and re-visit any location investigated by these rover teams.

The SDT reviewed the candidate sites proposed for MSL and for future missions to establish a set of stressor sites encompassing sufficient capability (threshold, baseline, and enhanced) to ensure potential range of high priority candidate sites could be evaluated. Table 8-3 lists the six sites identified by the SDT. Most importantly, four of the six are E2E-iSAG reference sites—Jezero, Nili Fossae, East Margaritifer, and N.E. Syrtis—and one—Holden—was among the final four candidates for the MSL mission. The sixth site—Melas Chasma—was included because it is a site of high astrobiological interest (e.g., Quantin et al. 2005) that also occurs in the Valles Marineris, a trough system that has been considered challenging to EDL systems. More information on these sites can be found in Appendix 7.

Stressor Landing Site	Stressing Parameter	Notes
Holden Crater	Latitude (-26°S)	Pushes southerly lat limits; TRN might enable "land on"
Jezero Crater	Rock Abundance	>1% failure without THA
Nili Fossae	Elevation (-0.6 km)	Landing ellipse ranges up to 0 km elevation, 6% area scarps
E Margaritifer	Inescapable Hazards	>3% of landing ellipse is inescapable, 99% success with 300 m divert
NE Syrtis	Scarps	>4% ellipse scarps, 99% success with 300 m divert
Melas Chasma	Landing Ellipse Size Wind	V. Marineris - Wind and Relief Issues?

† *TRN = Terrain-Relative Navigation; THA = Terminal Hazard Avoidance*

Table 8-3. Particular landing sites "stress" different aspects of the MSL landing system. *Reference landing sites with challenging attributes chosen in order to ensure that a range of high priority candidate sites could be evaluated during the landing site selection process*

Finding 8-10: Six potential landing/field sites are identified as "stressors" on landing capabilities and encompass a sufficiently large population of candidate sites (>60, see Table in Appendix 6) as to ensure high priority candidates remain as constraints evolve. These form an envelope which includes accommodation of the prior MER and MSL landing sites and many of the > 60 other sites between 30°N and 30°S that have proposed by the science community for MSL and future missions

Although relaxing the E2E-iSAG (2012) requirement of access to *in situ* unaltered igneous rock increases the number of viable candidate sites to > 60 (see Table in Appendix 6), it is clear from the suite of six stressor sites that many would still be inaccessible using MSL EDL capabilities ‘as applied’. For example, access to at least five of the six 2020 stressor sites would be precluded (leaving only Holden crater), thereby overly limiting the total number of sites that could be considered for the mission. Access to the Nili Fossae trough would be enabled with the higher landing elevations expected for 2020. Further, MSL EDL capabilities, as applied, would limit access in 2020 to only one aqueous sedimentary site and preclude access to high priority hydrothermal reference sites on the northwest rim of Isidis (and further limit the opportunity to access in place igneous). Therefore, it is concluded that MSL EDL capabilities as applied must be expanded, if possible, in order to maximize the range of candidate landing sites available to the 2020 mission.

Major Finding 8-11: MSL landing capabilities, as applied, limit the number and character of candidate sites than can be considered for 2020. Increase in landing elevation for 2020 would provide access to additional high priority candidate sites, thereby reducing science risks.

The sensitivity to the capability encompassed by the stressor sites could be evaluated by comparing changes in parameters to list of candidate sites in Appendix 6 and determining how quickly the number of viable sites diminishes with decreasing capability. A review of the candidate sites in Appendix 6 shows that ~10 sites would be lost if the permitted southerly landing latitude were reduced from 30°S to 15°S (the latitude constraint used by E2E-iSAG, 2012); the lost sites would include several deemed of high value for habitability/astrobiology objectives during the MSL site selection process, including two of the “final four” candidates, Holden and Eberswalde craters.

Further review indicates that ~7 proposed sites would be lost if the permitted landing elevation were reduced from –0.5 km to –1 km “as applied” from MSL; lost access would impact areas northwest of Isidis that were deemed of high value during the MSL site selection process, particularly the Nili Fossae site. Increasing the accessible elevation from –0.5 km to +0.5 km (unmargined value for 2020) permits access to ~4 additional sites (e.g., Antoniadi crater, at least one hypothesized chloride sites) and would be valuable if significant trades in payload or other access parameters are not required.

Finding 8-12: The threshold EDL requirements should include access to ±30° latitude and elevation up to –0.5 km in order to ensure access to a range of high priority sites for the 2020 mission. More high priority sites would be permitted with a baseline elevation up to +0.5 km. While additional high-priority sites are accessible at elevations above +0.5 km, this access is deemed “enhanced capability” and not critical.

8.3 Possible Additional EDL Capabilities for 2020

There are additional capabilities beyond the MSL ‘as applied’ that could greatly expand access to candidate landing sites for the 2020 rover mission, as revealed by the properties of the stressor sites (Table 8-2). These capabilities include options for reducing landing ellipse size and for avoiding hazards that may be present in the landing ellipse. Capabilities explored for Mars 2020 relate primarily to improved access afforded by Range Trigger, TRN, and THA; see Sections 3.6.2.1, 3.6.2.2, and 3.6.2.5 of this report. The discussion here focuses on landing site implications. Inclusion of one or more of these capabilities would result in costs that are incompletely understood; therefore any associated trades to mission capability or instruments required by their inclusion cannot yet be defined. Moreover, the science community has not had the opportunity to propose sites to the science requirements for the 2020 rover mission (i.e., are there astrobiologically significant sites that include in-place, unaltered igneous rock outcrops and what are the science trades if there are not?) and two years of additional data collection/interpretation would have been done on candidate sites since MSL.

At this time it is not possible to predict the full range and number of sites that would be proposed for the 2020 rover or what their relative priorities would be. Once there is a better sense of the range and number of sites proposed for the mission and there is a better gauge of the costs/trades associated with implementing additional EDL capabilities, more definitive statements could be made regarding the full set of threshold and baseline landing capabilities for the 2020 mission.

Finding 8-13: Additional EDL capabilities should be further explored. What might be implemented awaits further knowledge of required resources and impact to science.

8.3.1 Range Trigger

As described in Section 3.6.2.1, the MSL EDL system deployed the supersonic parachute at a pre-specified navigated velocity. This velocity-based trigger was selected for simplicity and resulted in the previously discussed landing error ellipse. To shrink the landing ellipse for the 2020 mission, the parachute deploy trigger could be changed to a range-based trigger, where the spacecraft waits until it believes it is over the desired target before deploying the parachute. This change to the EDL software is relatively simple, since the MSL system already has knowledge of its navigated position and requires no additional hardware.

Deploying the parachute using navigated position can substantially reduce the landing error ellipse size. Whereas a 25 km x 20 km margined ellipse (major axis x minor axis) would be used for a navigated velocity trigger, a Range Trigger could achieve an 18 km x 14 km margined ellipse. The velocity and Range Trigger capabilities are summarized in Table 8-4 below.

Capability	MSL As Flown	MSL + Range Trigger
	(margined)	(margined)
Landing Site Elevation	-0.5 km	Likely no effect
Ellipse Size (major x minor)	25 km x 20 km	18 km x 14 km
Hazards in Ellipse That Can Be Avoided	None	None
Landing Latitude Range	30°S to 30°N	No effect

***Table 8-4. Range Trigger considerably decreases the size of the landing ellipse, thereby enabling consideration of a broader range of landing site options*.**

The use of Range Trigger might degrade landing elevation capability for a small number of sites, especially if they are at or near the unmargined upper limit of the system's altitude capability. Further analysis of this potential issue is ongoing.

Note that landing ellipse error could be improved further for landing sites where wind uncertainty is believed to be small. At such sites, the ellipse might be as small as 13 km x 7 km; however, knowledge of wind uncertainties is usually not possible until deep into the landing site safety assessment process.

8.3.2 Terrain Relative Navigation (TRN)

Given the propellant that was available in the MSL EDL system (as flown), diverts of up to 300–500 m may be possible with Mars 2020. To account for this limit and allow some position determination uncertainty, it is expected that a TRN enhanced EDL system could accommodate 150 m radius hazards in the landing error ellipse as long as they are surrounded by safe areas of at least 100 m in radius. This is summarized in Table 8-5, below.

Capability	MSL As Flown (margined)	MSL + TRN (margined)
Landing Site Elevation	-0.5 km	Likely no effect
Ellipse Size (major x minor)	25 km x 20 km	No effect
Hazards in Ellipse That Can Be Avoided	None	Up to 150 m radius hazards bounded with safe areas ≥ 100 m radius
Landing Latitude Range	30°S to 30°N	No effect

Table 8-5. Terrain Relative Navigation would enable landing at a large number of science targets of high priority to the objectives of Mars 2020. The third row of the table is critical.

The use of terrain relative navigation might degrade landing elevation depending on the size of divert needed to accommodate the largest hazards in the ellipse, but only for sites at or near the unmargined altitude capability of the system.

8.3.3 Terminal Hazard Avoidance (THA)

Examples of rover-scale hazards that might be not be observable in orbiter images include rocks and small-scale high slopes. Note that given the scale of the rover, only rocks greater than 0.55 m height are hazardous; MRO HiRISE images have typically allowed identification of rocks down to 0.75 – 1.0 m (Golombek et al. 2008; Golombek et al. 2012).

To ensure that the vehicle could reach safe location, rover scale hazards would need to be surrounded by safe areas greater than 2.5 m in radius. The envisioned THA capability is shown in Table 8-6 below.

Capability	MSL As Flown (margined)	MSL + HA (margined)
Landing Site Elevation	-0.5 km	No effect
Ellipse Size (major x minor)	25 km x 20 km	No effect
Hazards in Ellipse That Can Be Avoided	None	Rover scale hazards bounded by safe area ≥ 2.5 m radius
Landing Latitude Range	30°S to 30°N	No effect

Table 8-6. Terminal Hazard Avoidance has a smaller affect on hazard avoidance than does TRN.

8.3.4 Mapping Additional Capabilities to Landing Site Access:

Range trigger is an EDL capability could be added to substantially reduce ellipse size as described above. The result could be granting access closer to or, in some instances, within locations previously inaccessible to the EDL system. Addition of Range Trigger capability to Mars 2020 would allow for a substantially smaller ellipse (e.g., 13 km x 7 km with low wind uncertainty), which would permit access to additional sites (e.g., Melas Chasma), and could convert some "go to" sites to "land on or nearly on" (e.g., Gale crater, East Margaritifer Chloride, Eberswalde crater, Holden crater), thereby greatly reducing traverse distances and duration to some sites. Note that most of the ~15 final candidate sites for MSL (see Grant et al. 2011) required traverse distances of > 5 km to get to science targets. This assumes that the addition of Range Trigger capability has little impact on mission resources.

A smaller ellipse size would place the rover much closer to high priority science targets, thereby greatly reducing the time and distance needed to access them after landing. As is described in Section 7, reducing the traverse time and distance after landing could be enabling when it comes to achieving mission goals. Hence, Range Trigger is an attractive addition to EDL capability for multiple reasons.

Figure 8-3 shows the potential reduction in landing ellipse size that might be achieved using Range Trigger. The resulting low wind uncertainty and 13 km by 7 km ellipse could be placed much closer to the primary science targets associated with Mt. Sharp in Gale crater, thereby greatly reducing the likely traverse distance for access and converting valuable prime mission time into interrogation of rocks rather than driving. Addition of TRN yields additional benefits that could convert Gale crater from a "go to" site to a "land on" site.

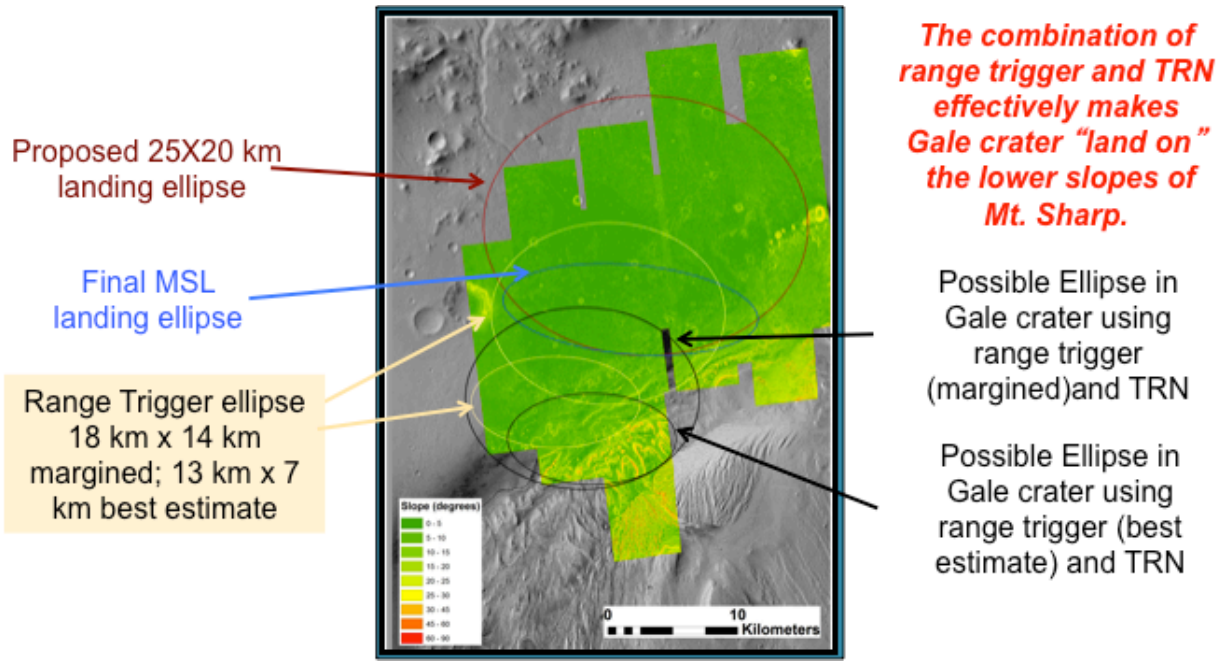


Figure 8-3 Comparison of MSL "as flown" capabilities and the improvements provided by various potential new technologies*. Original landing ellipse for MSL (red) and final ellipse (blue), leaving MSL with an ~8-km traverse to its primary science target. Range Trigger would have reduced the landing ellipse size (yellow), resulting in only a few km traverse. TRN would have enabled rougher terrain inside the ellipse (lower yellow), and the primary science target would have been inside the ellipse. From Matt Golombek, personal comm. 2013.*

TRN may enable access to previously inaccessible high priority sites. TRN would be enabling for 2020 to reach some high priority sites thought to emphasize hydrothermal conditions (e.g., NE Syrtis, Mawrth, E. Margaritifer Chloride). This is especially relevant to the region to the west and northwest of Isdis basin that includes the NE Syrtis Reference Site. At this and other sites, hazards distributed as relief (e.g., craters, small mesas) throughout the ellipse represent unacceptable risk to the MSL "as applied" system and resulted in these intriguing sites being removed from consideration during the MSL site selection process. The scale of the hazards in NE Syrtis are such that TRN would remove many of them and significantly reduce the scale of others, thereby making the distributions of hazards much less and lowering the risk associated with landing to acceptable levels. Because TRN is relevant to a number of sites, and especially those interpreted as granting access to sites with classes hydrothermal deposits, it is viewed as a very important capability for the 2020 mission.

THA (see Section 3.6.2.5) is another capability that should be considered. This is particularly important for sites where there are hazards, such as rocks, in the vicinity of the high priority science targets. A primary benefit of THA is to reduce the required rover traverse required for target access. However, there may be additional sites where access is only possible with capability afforded by THA. An example of the latter is the candidate fluvial delta site in Jezero crater (an E2E-iSAG and 2020 reference site), where abundant rocks and small-scale relief associated with probably volcanic deposits on the crater floor (Fig. 8-4) preclude landing there without THA. Although THA is viewed as a valuable asset, it is lower in priority than Range Trigger and TRN.

8.3.5 Proposed 2020 EDL Capabilities

When mapping the potential EDL capabilities against the 2020 Reference Sites, the value of the Range Trigger and TRN enhancements becomes apparent. For sites for which we have sufficient orbital image coverage, an assessment of the landing hazard has been conducted for the as-flown MSL capability and for the cases that would include addition of EDL technology enhancements (Table 8-7). Green circles indicate landing failure rates of approximately 1% or less, which is in line with what was found for the four MSL candidate landing site finalists. Yellow circles indicate landing failure rates of approximately 1–5%, commensurate with the original landing failure rate accepted in the original MSL requirements. Red circles indicate failure rates exceeding 5%. All assessments are very preliminary and based heavily on engineering judgment; detailed hazard maps of all sites have not yet been created.

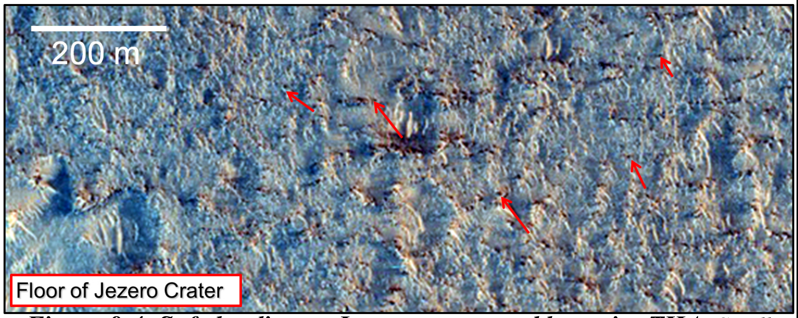


Figure 8-4. Safe landing at Jezero crater would require THA. *Small-scale terrain hazards. A portion of the floor of a suggested MSL landing site, the floor of Jezero Crater. The red arrows highlight the location of example rocks and other meter-scale topographic hazards. Safe landing at this site would require THA (terminal hazard avoidance) capability. Portion of HiRISE image PSP_007925_1990. JPL/NASA/University of Arizona.*

A maximum landing site elevation of -0.5 km MOLA is proposed as the threshold requirement. This provides the mission with adequate development margin while preserving access to most high value sites.

A threshold landing error ellipse size of 18 km x 14 km (major x minor) is proposed; this assumes that the incorporation of Range Trigger is a threshold capability. As discussed previously, it is likely (although not guaranteed) that the ellipse size would shrink during the development and site selection process.

Reference Landing Site	Stressing Parameter	MSL As Flown	MSL+ Range Trigger	MSL + Range Trigger + TRN	MSL + HA	Notes
Holden Crater	Latitude (-26 ˚S)	🟢	🟢	🟢	🟢	Pushes southerly lat limits, TRN might enable "land on"
Jezero Crater	Rock Abundance	🔴	🔴	🔴	🟢	>1% failure without HA
Nili Fossae	Elevation (-0.6 km)	🟡	🟢	🟢	🟡	Landing ellipse ranges up to 0 km elevation, 6% area scarps
E Margaritifer	Inescapable Hazards	🔴	🟡	🟢	🔴	>3% ellipse inescapable, 99% success with 300 m divert
NE Syrtis	Scarps	🔴	🟡	🟢	🔴	>4% ellipse scarps, 99% success with 300 m divert
Melas Chasma	Landing Ellipse Size, Wind	🔴	Not Assessed	Not Assessed	Not Assessed	Constrains ellipse size in V. Marineris - likely wind and relief issues?

🟢	Similar to MSL as flown (≤ 1% terrain failure)
🟡	In family with MSL requirements (≤ 5% terrain failure)
🔴	Out of family with MSL requirements (> 5% terrain failure)

Table 8-7. MSL + Range Trigger + TRN has greater impact than MSL + HA. *Mapping of EDL Augmentation Options Against Reference Landing Sites.*

Given that several landing sites contain hazards in the landing ellipse, TRN is proposed as a baseline capability for 2020. This would allow up to 150 m radius hazards to be present in the landing ellipse as long as each is surrounded by a safe area of greater than 100 m radius. The TRN capability is not included in the proposed threshold because it is not yet clear that the capability is absolutely necessary to achieve the overall mission objectives and because of the development and cost risk associated with TRN. THA is a possible enhancement of lower priority TRN. The proposed EDL capabilities are summarized in Table 8-8.

	Threshold With Range Trigger	Threshold With Range Trigger + TRN
Landing Site Elevation	-0.5 km	-0.5 km
Ellipse Size (major x minor)	18 km x 14 km	18 km x 14 km
Hazards in Ellipse That Can Be Avoided	None	Up to 150 m radius hazards bounded with safe areas ≥100 m radius
Landing Latitude Range	30°S to 30°N	30°S to 30°N

Table 8-8. The addition of both RT and TRN to the current MSL landing capabilities would enable a far wider range of acceptable landing sites than has been possible in the past.

Finding 8-14: The SDT concludes that Range Trigger should be a threshold capability and strongly proposes inclusion of TRN as highest priority baseline so as to help ensure access to a sufficient number of high priority sites and reduce science risk related to site selection. Access to an equivalent number of aqueous sedimentary and hydrothermal landing targets likely requires both Range Trigger and TRN to be implemented. Terminal Hazard Avoidance has less impact on access to unique classes of sites and is considered "enhanced."

8.3.6 Implementation Considerations for Potential EDL Augmentations

The potential EDL augmentations under consideration vary widely in cost, implementation risk, accommodation impact, and mission risk.

Range trigger does not require any new hardware and even the software modifications required are minor: the MSL EDL system already computes navigated position and triggering algorithm is simple. Thus, the implementation risk and accommodation impact are very low. The cost and mission risk are all incurred in performing analysis and testing to confirm trigger performance and develop a tuning strategy.

TRN would require new hardware including a camera and a dedicated set of flight qualified avionics to perform the required image correlation. Although no new sensor technology needs to be created, the need to space-qualify hardware and execute field testing drives up the cost and implementation risk. Some mission risk is also introduced when depending on TRN and accepting hazards in the landing ellipse; however, it is believed that TRN could be integrated in a "fail-safe" manner such that the landing risk is no worse than MSL landing capability. The TRN related hardware would likely be mounted on the rover, where several different accommodation options exist and appear to be similar to that of the MSL Mars Descent Imager (MARDI; Malin et al. 2009), in terms of resources needed. Thus, accommodation impact is moderately low.

Augmentation of the EDL system for THA would require new LIDAR sensor development in addition to hardware space-qualification and field testing. As a result, development cost and implementation risk are expected to be high. Hazard avoidance also requires a tighter coupling to the EDL system than the other options under consideration. Rather than just update the estimated position like TRN, hazard avoidance needs to identify safe and hazardous terrain during flight and fly the vehicle to a reachable safe location. By nature, safe locations cannot be identified a priori on the ground. Additionally, the powered flight software needs significant modifications to integrate hazard detection and avoidance. Thus, the mission risk is higher than the other augmentation options. Physical and avionics accommodation of the THA system is likely similar to the TRN system, although the sensor immaturity may introduce additional accommodation impact.

A qualitative summary of cost, implementation risk, mission risk, and accommodation impact for each augmentation option is presented in Table 8-9 below.

Table 8-9. Qualitative Assessment of EDL Augmentation

	Cost	Implementation Risk	Mission Risk	Accommodation Impact	Notes
Range Trigger	Low	Low	Low	Very Low	No Rover resources req'd
TRN	Medium - High	Medium	Low - Medium	Low - Medium	Requires MARDI-like resources on Rover*
HA	High	High	High	Medium	Requires MARDI-like resources on Rover*

*Will compete for surface science volume.

Preserving the option to accommodate the EDL augmentations consumes increasing amount of resources as the project development proceeds. Early costs associated with technology development, requirements definition, and accommodation studies are relatively low; the vast majority of resources are consumed during later development and testing after project PDR, particularly for the options that add hardware. Obviously, the earlier an option is descoped the lower the costs. This is summarized in Table 8-10 below.

Table 8-10. Estimate of Percentage of EDL Augmentation Resources Consumed During Development

	Now Through SRR (7/14)	SRR to PDR (7/15)	PDR to Launch (7/20)	Notes
Range Trigger	~ 15%	~ 25%	~ 60%	Total cost expected to be significantly lower than other options
TRN	< 5%	~ 25%	~ 70%	Field test required
HA	< 5%	~ 15%	~ 80%	Field test required

8.3.7 Conclusions Regarding Additional EDL Capability for the 2020 Mission:

Summary Statement Regarding Science and EDL Capability for the 2020 Mission:

In order to maximize science potential at the eventual landing/field site for the objectives of the 2020 mission, access to >60 astrobiologically relevant candidate landing sites is viewed as a threshold requirement. Access to *in situ* volcanic rocks is viewed as baseline capability and would enhance the science return of the 2020 mission, but may unduly limit the number of candidate landing sites (to ~10).

With respect to engineering constraints, in order to access >60 candidate sites, MSL threshold landing capability "as applied" needs to be enhanced by access to -0.5 km elevation. A smaller ellipse size afforded by Range Trigger is also considered threshold. The inclusion of TRN enables access to both subaqueous sedimentary and hydrothermal sites and is considered baseline pending initial assessment of required resources and associated trades. Addition of THA to gain better access to sites characterized by local relief/rocks is viewed as enhanced capability and should be explored. The SDT suggests that the 2020 project provide a schedule that could be used to better define threshold capabilities, thereby helping to guide site selection without incurring significant expense.

Finding 8-15: The expertise of the science community can assist in making critical decisions about landing sites, early enough in the mission design phase to limit costs for capabilities that are not adopted (e.g., if community consensus finds that sites that need TRN can be eliminated from consideration for a Mars 2020 landing site, then TRN can be descoped before incurring significant costs).

8.4 Statement on Access to Special Regions

There are two types of Planetary Protection defined special regions on Mars: A) naturally-occurring special regions (i.e. those where the threshold conditions are violated naturally); and B) induced special regions—places where a heat source could cause the threshold conditions to be violated (SR-SAG 2006). These apply to areas where water or water-ice is suspected to be present within ~one meter of the surface. Special regions are so named because of what they represent in the modern environment (e.g., recurring slope lineae; McEwen et al. 2011), so they do not apply to the 2020 mission objectives because the Science Definition Team charter states the overarching mission objective is to "Explore an astrobiologically relevant ancient environment on Mars."

Despite this statement, there may be landing sites where the primary science targets are accompanied by landforms suspected to harbor ice, or other deposits that could comprise an induced special region in the presence of a heat source associated with a rover. For example, the Ismenius Cavus E2E-iSAG Reference Site includes a region where the presence of lobate aprons around some hills (Dehouck et al. 2010) could represent local ice deposits (e.g., Holt et al. 2008) within or near the proposed landing ellipse. If these interpretations are correct, such lobate debris aprons would be considered Special Regions. However, a review of candidate sites proposed for MSL and possible future opportunities (Appendix 6) reveals that many suggested field sites appear to involve no complications related to Special Regions.

Finding 8-16: The 2020 mission would have no need to go to a naturally-occurring or included Special Region; per the charter of the 2020 SDT, the 2020 rover would explore an ancient environment, and there are many such candidate sites that do not include special regions.

8.4.1 Critical Importance of Community Site Selection

The science community defines what are the highest priority geologic materials. The prospectus for a site accessible to the Mars 2020 rover that must address Objectives A, B, C, and D might look somewhat different than that of previous landed and rover missions. The science community has not been directly presented with a real mission to Mars that would both collect and cache an array of samples for eventual return to Earth (Objective C) and seek biosignatures and characterize biosignature preservation potential (Objective B). Would the optimum site be one that is on the list of sites previously suggested for MSL, ExoMars, and other missions (Appendix 6), or would there be an emergent, leading candidate of which very few science community members are presently aware? If the Mars 2020 EDL and/or Mobility systems are altered, relative to the as-flown MSL systems, would new candidate sites emerge which have not previously been discussed because they were thought to be inaccessible?

The E2E-iSAG Reference Sites were considered to be candidates that might address Objective C, and many dozens of sites have been suggested (Appendix 6) that might meet some or all of the A, B, C, and D objectives of the Mars 2020 mission, but the SDT does not know exactly what the result would be when the science community is asked to select a site that addresses these specific objectives. Further, many candidate sites, including a few of the E2E-iSAG sites, might require deeper study than has previously been performed. In some cases, new data from orbiting assets might have arrived on Earth since the last time someone made an effort to investigate a given candidate site; further, new data analysis tools or capabilities might exist that were not available when investigators last considered a given site several years ago.

A science community priorization process is required to help select the site for this mission and help NASA and the Mars 2020 project make critical, early decisions that would influence mission design and final site selection. The SDT strongly suggests that NASA provide the resources for candidate sites to be investigated by the science community and for scientists to meet and discuss the suite of candidate sites at a series of site selection workshops. Of critical importance would be the first workshop, which would need to occur early enough in calendar year 2014 so that its results could inform key project decisions regarding whether to modify the as-flown MSL entry, descent, and landing (EDL) system and/or the rover mobility system to provide access to the types of sites of high interest to the science community within the operational constraints of a 1-Mars-year Primary Mission.

The SDT endeavored to ensure that a wide range of candidate sites would be available for the initial discussions in 2014. From there, science community input would begin to help narrow and focus the list on the most accessible highest priority candidate sites.

Before the first landing site workshop in 2014, the goals of this workshop should be fully explained to the science community; the outcome could include project cost savings. One objective is to survey the community's knowledge of ideal sites for the Mars 2020 mission—where could the mission simultaneously address Objectives A, B, C, and D? Further, a major goal of this first workshop must be to understand the options for and implications of modifying the as-built MSL EDL and Mobility systems. What is to be gained, for example, and what is lost, by considering addition of EDL capabilities such as Range Trigger, TRN and THA? Are such modifications necessary to reach the sites that the community currently (in early 2014) thinks would be the best for addressing the Mars 2020 objectives?

Finding 8-17: The SDT believes that to understand the technical need for additional EDL capabilities, it may be necessary to begin the landing site selection process in 2014.

Finding 8-18: Mars 2020 would be the first mission to cache samples for possible return to Earth and may require a landing site selection process differing from those previous and tailored to a diverse set of scientific goals. It is therefore crucial to involve the broad expertise of the science community in proposing and evaluating candidate sites for the 2020 rover, thereby leading to science community consensus on the optimal site for meeting the mission goals.

9 Mars 2020 Rover Strawman Spacecraft Technical Overview

Figures 9-1 and 9-2 are presented as a schematic summary of the threshold and baseline scientific attributes of the rover, based on Sections 3 through 8 above.

The Mars 2020 rover project would…

…be cost-effective by reusing proven technology from Curiosity's successful landing on and exploration of Mars.

The Mars 2020 flight system design concept is described at a high level in this section. The design presented is a notional reference design that was converged upon for the purposes of assessing the feasibility of the options considered by the SDT. To this end, flight system resources were assessed in terms of mass, power and volume. Due to the fact that the vast majority of the design changes from MSL are related only to the rover, this is where the feasibility assessment was focused. However, the flight system as a whole is described below for completeness.

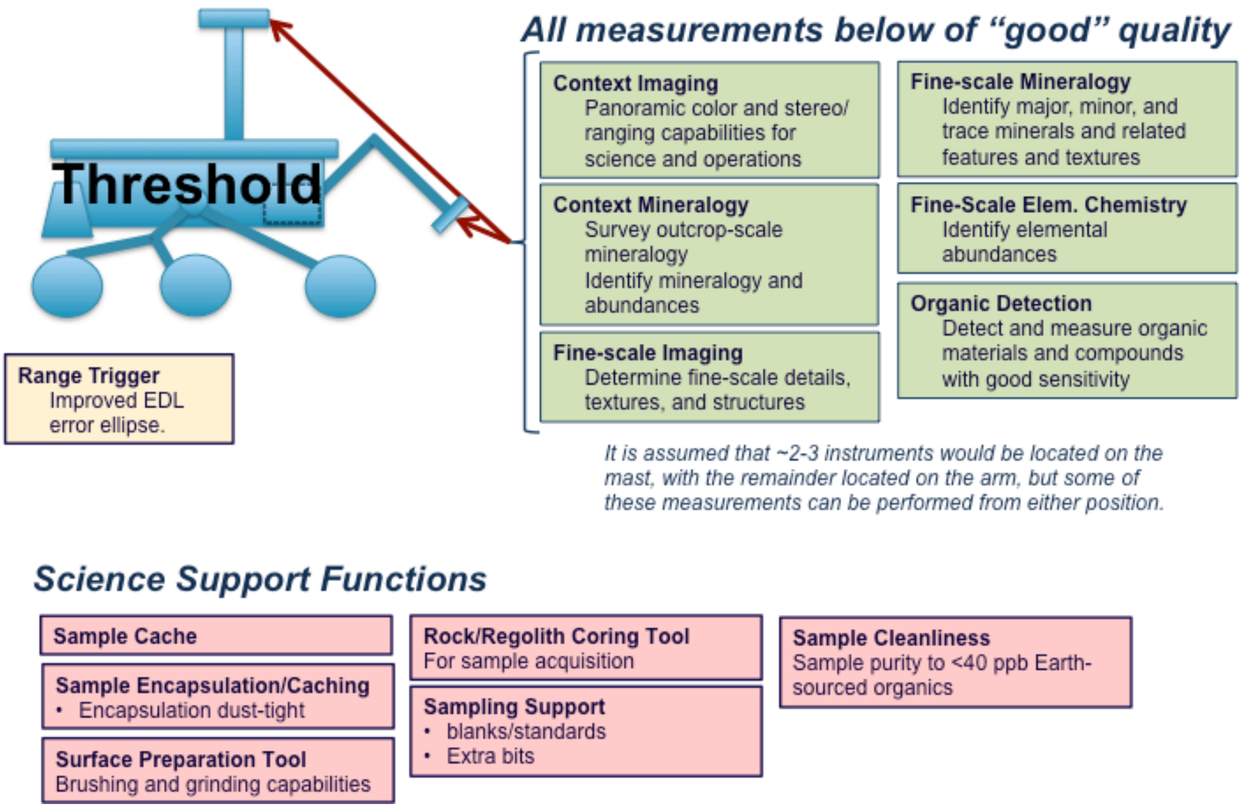


Figure 9-1 Summary of the primary science attributes of a THRESHOLD rover. *The 6 measurements that must be included in the rover are described, plus Range Trigger, a sample cache, surface preparation tool and rock/regolith coring tool.*

The flight system concept is divided into two major functional elements: 1) the cruise, entry, descent, and landing (CEDL) system and 2) the rover. The rover would be delivered to the Mars surface by the CEDL system directly inherited from MSL. The design intent for the 2020 rover is to maximize heritage from the MSL rover system as well -especially avionics, telecom, mobility, and CEDL interfaces (mechanical and electrical). The integrated 2020 flight system would be launched on an Atlas V541 or 551-class launch vehicle.

9.1 Cruise, Entry, Descent, and Landing (CEDL) System

Per the heritage MSL mission concept, the cruise stage of the CEDL system would deliver the EDL stack (including rover) to Mars, release them prior to entry, and burn-up in the atmosphere (Fig. 9-3). The cruise stage is envisioned to be the same design used for MSL, as trajectory characteristics are sufficiently similar for the 2020 opportunity as for the 2011 MSL launch. The spacecraft would be spin-stabilized throughout cruise. The cruise heat rejection system mechanical pump and fluid loop would be used to distribute heat throughout the cruise, EDL and rover stages until cruise stage separation.

The aeroshell and parachute systems, consisting of the heatshield, backshell, parachute, and cruise and entry balance masses, are assumed to be identical to the MSL system (Fig. 9-3). Like MSL, guided entry aeromaneuvering would be performed by banking the entry vehicle to produce desired down-track range and thus reduce the landing error ellipse. The system would provide identical or possibly slightly improved EDL communication capabilities, intending to use both Mars relay links and direct-to-earth links as available. At approximately Mach 2, the parachute would be deployed. Once the vehicle has achieved subsonic velocity, the heatshield is separated. At ~1.6 km altitude, the descent stage and rover are separated from the backshell and parachute, initiating powered flight.

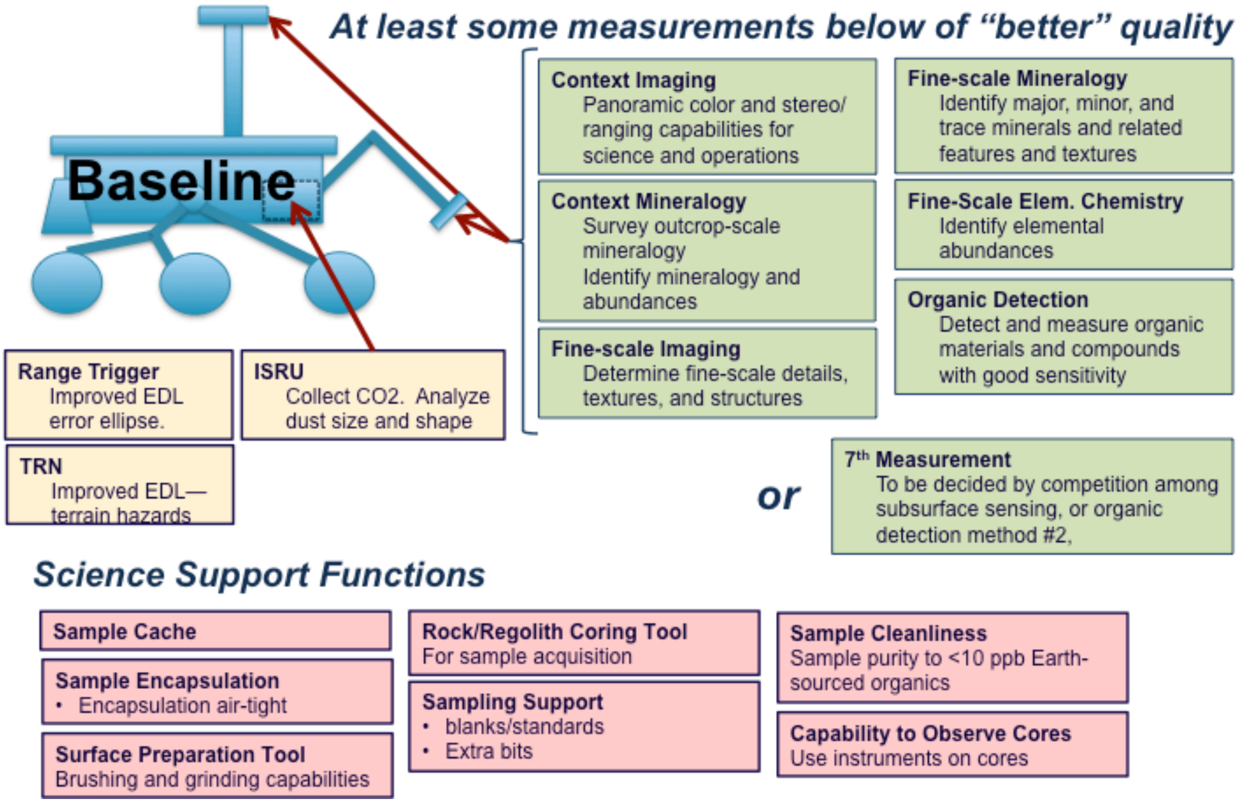


Figure 9-2 Summary of the primary science attributes of a BASELINE rover. *The desired measurements for the rover could be increased in performance with additional funds, or a seventh measurement could be included. TRN and an ISRU demonstration are also desired. Viewing the cores prior to putting them in a cache is also highly desirable.*

The descent stage design is also assumed to be identical to MSL (Fig. 9-3). An inertial measurement unit (IMU) would be used for guidance with reference to initial entry point, and the MSL terminal descent radar would be used for line-of-sight range and velocity measurements. The rover, attached to the descent stage, would be released and lowered to the surface on bridles in a Sky Crane mode. Once the rover has touched down, it would cut the bridles and the descent stage would fly away to a safe distance and impact the surface.

Options for EDL augmentation exist and may be considered. Options include the use of a Range Trigger to deploy the parachute, instead of the MSL heritage velocity trigger. This change could reduce the size of the landing ellipse. Another possible EDL augmentation is the addition of a TRN system to the rover to allow safe landings at hazardous sites (see material in Landing Site discussion, Section 8).

9.2 Mars 2020 Rover: Modifications from MSL

The majority of the Mars 2020 rover support equipment would be inherited from the MSL rover, including the mobility system, avionics, communications, engineering cameras, remote sensing mast, and interface to the descent stage. Like its predecessor, the Mars 2020 rover would be designed for at least a 1 martian year primary surface mission and a total traverse capability of at least 20 km. The redundancy approach on the 2020 rover would be identical to the MSL Rover, which includes redundant computers relay radios, IMUs, and engineering cameras. Like MSL, the baseline 2020 rover would use a MMRTG nuclear power source that would provide 110-115 W of continuous power.

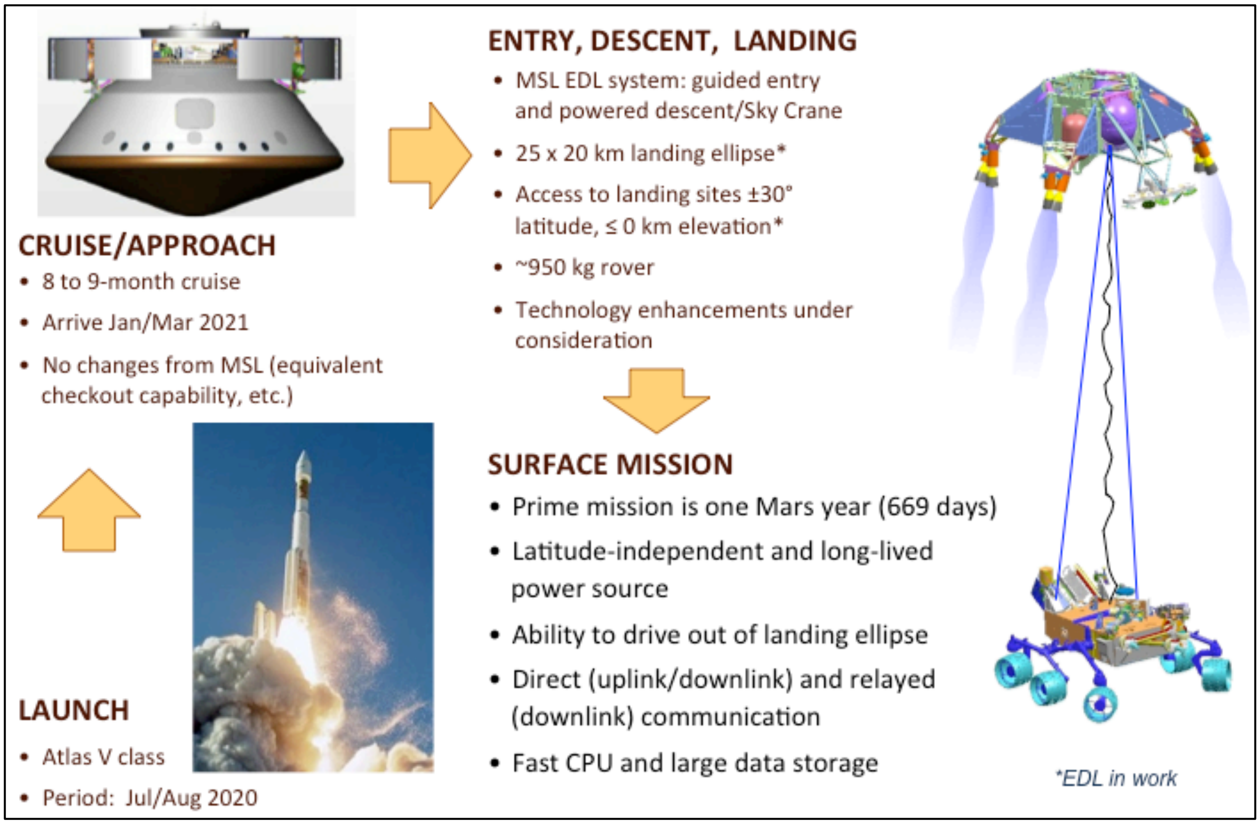


Figure 9-3 Proven MSL-heritage landing technology.

The primary change to the MSL heritage rover design would be the removal of the MSL science instrument suite and replacement with the 2020 payload - both instruments as well as the sampling mechanisms. As described in Section 5 of this report, and summarized in Figures 9-1 and 9-2, the SDT has designed a threshold level strawman payload and a baseline level strawman payload, each of which consists of two alternate instrument sets ("blue" or "orange" payloads, Table 5-3). The threshold level strawman payload (Fig. 9-1) consists of:

- One of the two alternate science instrument sets.
  - The science instrument component of the "blue" strawman payload is made up of the following instruments (or similar to these): MastCam, UCIS, MAHLI, APXS, and a green Raman spectrometer.
  - The "orange" one is comprised of the following instruments (or similar): MastCam, Mini-TES, MMI, micro-XRF, and a deep UV spectrometer.
- Science support equipment elements that include sampling system (including encapsulation, blanks/standards, extra bits, and adequate sample cleanliness), cache, and a surface preparation tool
- Technology payload elements that include Range Trigger

The baseline level strawman payload (Fig. 9-2) consists of the above, plus:

- An additional science instrument option (represented in Table 5-3 as GPR) OR enhanced-capability instrument from threshold instrument sets (see Table 5-1)

- Science support equipment that includes the capability to observe cores using the instruments on the rover AND/OR better sample cleanliness
- An HEO contributed payload (represented in Table 5-3 as ISRU)
- Technology payload elements that include TRN

From analysis of known instrument analogues (existing instrument designs and concepts, for science measurements identified by the SDT), it has been determined that from a flight system accommodation standpoint, the "blue" and "orange" strawman instrument sets are nearly indistinguishable. They have almost identical mass (15.5 kg vs. 15.3 kg), volume (mast, arm, and body requirements) and accommodation needs (power, etc). Therefore, the configuration views and later mass values shown below are reflective of both sets of science instruments.

Design changes to the MSL heritage system that would allow for increased mission robustness and greater landing site flexibility have also been considered. The 2020 rover concept presented here includes both a notional TRN (of interest to the landing site community) and Direct-To-Earth communications capability augmentation (to backup UHF relay communications), as a way to preserve engineering margin in the system design along with the new science and HEO payloads.

For the addition of TRN capability, this would require the accommodation of two internal electronics assemblies: the TRN Compute Element; and a TRN IMU. A downward looking descent imager (akin to MSL's MARDI camera) would be required as well. The TRN hardware would utilize on-board image processing to more precisely determine the rover's local position within the initial landing ellipse based on previously-supplied high-resolution imagery taken from orbiters. This would allow the decent stage to fly the rover towards one of several predetermined safe landing zones within the larger ellipse. Therefore, with TRN the rover would potentially be able to land safely in landing ellipses which would otherwise not be considered due to excessive landing hazards.

The purpose of a Direct-to-Earth (DTE) communication capability augmentation would be intended to ensure a robust mission even in event that the UHF Mars relay network is degraded or non-functional at some point during the 2020 surface mission. The following changes to the MSL design would be required for this augmentation: replace the MSL HGA and gimbal with a larger "Super HGA" and necessary support equipment; and then to also replace the MSL rover power amplifier with a larger, traveling-wave-tube (TWTA) style amplifier (along with necessary cabling upgrades). The combination of the larger antenna aperture and the additional transmit power available would allow for much higher bandwidth on the direct-to-earth link. Similar to the EDL augmentation options, these changes have not been confirmed by the project, but the system resources to enable them are being protected by placeholders in the flight system design assumed here.

9.2.1 Special Accommodation Concerns

The Biomarker Detector System was identified in Table 3-11 as being at a third level of priority. This was in part due to several perceived challenges. The Biomarker Detector System would be a high cost payload, with significant impacts to the rover design, and low crossover with the science objectives of the Mars 2020 rover. These issues taken in aggregate indicate that there is very little chance of making the Biomarker Detector System work for this mission.

- The SDT charter specifies that a contributed HEO instrument must be "compatible with the science payload and within the mission's payload capacity." A Biomarker Detector System would raise concerns on both fronts. The science intent of the Biomarker Detector System (to assess the presence of *extant* biomarkers) could be done more effectively with returned samples than *in situ*, and indeed has low cross-over with the science objectives of the Mars 2020 rover (which focuses on *ancient* biomarkers).

- From an engineering perspective, the Biomarker Detector System would be difficult to accommodate. It is a large payload that would be difficult to accommodate given the constraints on the internal rover configuration. It would require a sampling system that delivers a powdered sample to the instrument (as opposed to sample requirement for simple cores), which would require at least $10M in additional accommodation costs and would stress robotic arm turret design and volume constraints. The instrument options for the Biomarker Detector System are not very mature, adding to the development and accommodation risk. The additional of a payload that requires unique sampling would add complexity to the surface operations scenarios and further stress the mission timeline. Finally, an extant life detection instrument would likely impact the missions Planetary Protection requirements (see Section 10), which could have significant implications for the rover design.

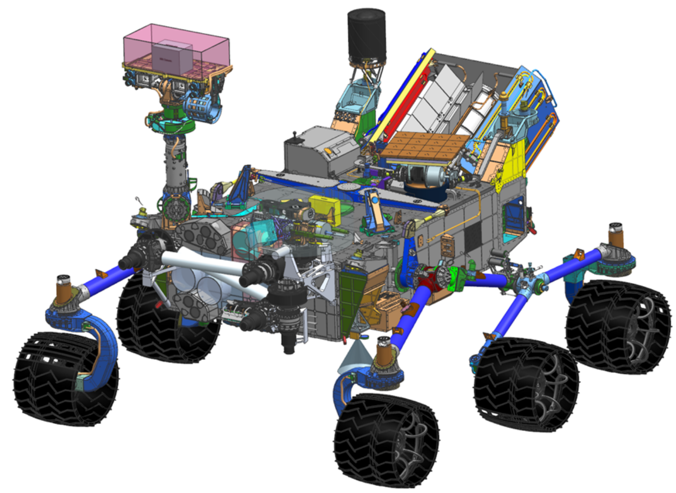


Figure 9-4. 2020 rover External Configuration concept with a potential MSL-heritage MMRTG power source.

9.3 Accommodation Assessment

9.3.1 Volume

For all the proposed changes, first order accommodation assessment would be volumetric - that the notional new equipment and their accommodation requirements do not break the existing system envelope. Figure 9-1 and 9-2 show the external and internal configuration of a 2020 rover, which includes concepts for the SDT-proposed instrument suites (enveloping both Blue and Orange concept suites) as well as the HEO ISRU and then the engineering upgrades (TRN and DTE augmentation).

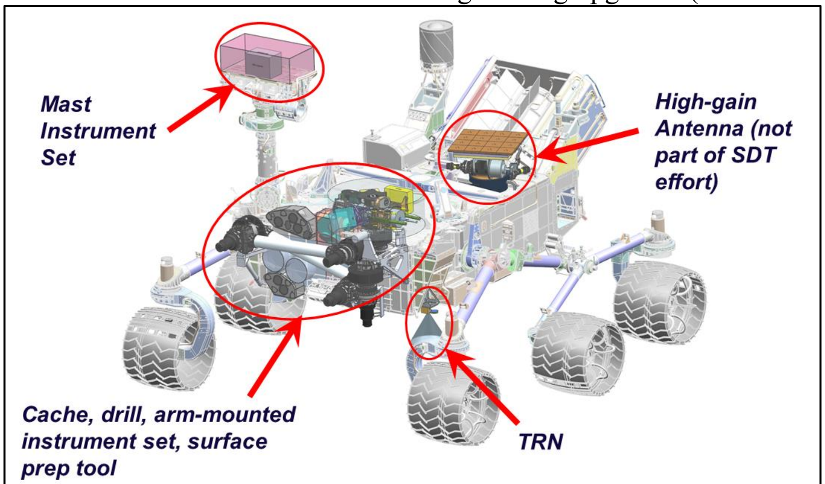


Figure 9-5. Proposed Mars-2020 rover showing the large extent of heritage from MSL (gray), and the several areas where significant departures from MSL heritage are envisioned

In this external view of the rover (Fig. 9-4 and 9-5), several of the proposed new 2020 features can be seen. At the top of the remote sensing mast, the MSL ChemCam would be replaced with UCIS or Mini-TES-like instrument (shown as cube on top of mast top plate). The new DTE augmentation high-gain antenna sits in the same place as the MSL antenna, and has been expanded in area. The front of the rover shows the notional new sampling arm and turret, with cache and bit boxes located within the front panel of the rover behind the stowed arm.

> **Major Finding 9-1:** This mission concept preserves maximum MSL heritage. The payload and a few specific elements (shown in Fig. 9-5) are unique to the Mars 2020 rover concept.

Figure 9-6 shows the internal configuration of the rover concept with MSL instruments removed and 2020 payload and engineering boxes fit within the newly exposed bays. Much of the space in the front of the rover, which would have contained the SAM and CheMin instruments, is now taken up by the cache, bit boxes and the ISRU payload. There is some room taken up by the bigger footprint of the DTE amplifier, and some space taken by payload control units for which the actual sensing elements are external to the rover.

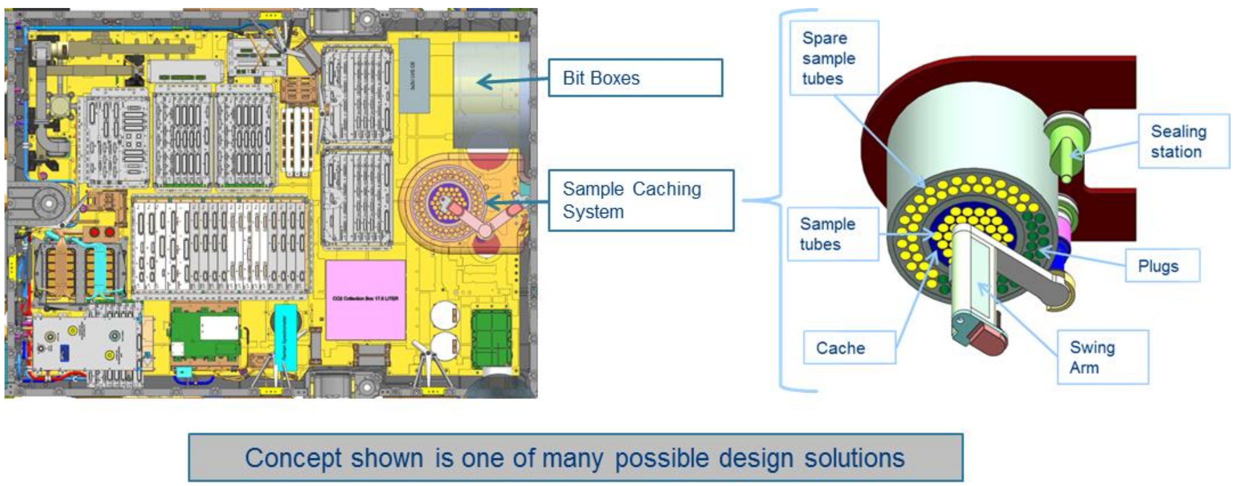


Figure 9-6. Sampling system and location on the Mars 2020 rover concept. Left: Example 2020 rover Internal Configuration. Right: Notional concept for a sampling and caching system.

Objective C of the SDT charter would require the accommodation of a sampling system as part of the 2020 payload - the notional concept for that is shown here (Fig. 9-6). As currently envisioned, the sampling system would be located near the front panel of the rover and be comprised of the following elements: a sample caching system (including a cache canister, sample tubes, plugs, and transfer mechanism); a robotic arm with turret-mounted sample acquisition tool; bit boxes for coring, brushing and abrading bits; and organic check material.

Note that the turret would also be the place for any fine-scale instruments ultimately selected, for example, APXS or a green Raman spectrometer.

The above conceptual mechanical drawings of 9-4 through 9-6 show that to first-order, the internal/external volume of the notional rover is adequate to accommodate the new payloads and engineering upgrades.

9.3.2 Mass

Another key consideration is mass. The 2020 concept changes from MSL impact the rover total mass and required margins far more than the launched total mass, as the CEDL system far outweighs the rover. The 2020 rover concept size is very similar to the MSL as-built system.

9.3.3 Power

The last key aspect of accommodation would be power to run the necessary science observations. On the surface, unlike in cruise, available energy must be matched to the particular set of activities run during the sol, which is highly dependent on the operational concepts and tactical time line.

9.4 Summary Flight System Assessment

In summary, based on current knowledge of measurement and payload technologies, the SDT-proposed Threshold instrument suite, and most of the Baseline suite, all fit to first order within the existing heritage MSL concept for volume, mass and (as seen in operational concepts) energy profiles. These payloads include options for the notional Orange and Blue strawmen instrument suites, possible new engineering and EDL upgrades, and possible HEO equipement. The one remaining Baseline option of GPR was not specifically addressed in this accomodation study, and so future work would be required to assess its feasbility within the heritage MSL system.

In addition to the physical parameters explicitly addressed in this section, control and monitoring for these new devices may be assumed to be similar enough to MSL experience that the number of power switches, telemetry and command ports, memory buffers, etc., may be also assumed to be adequate.

10 Planetary Protection

In order for a sample cache to be returnable, it would be required to meet planetary protection requirements deriving from NASA policy (NASA, 2008) and procedural requirements (NASA, 2011). The implementation approach would be among the challenges to be met by the mission engineers.

The Outer Space Treaty of 1967 states that parties shall conduct exploration of other celestial bodies "so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and where necessary, shall adopt appropriate measures for this purpose." Planetary protection policy has been translated into a categorization of missions according to type (*e.g.,* flyby, lander) and the interest of the target object for the understanding of the origin of life. The following designations are relevant to Mars sample return, with text drawn from the current NASA requirements document (NASA, 2011):

The Earth return portion of a Mars Sample Return mission is classified as "Restricted Earth return," with all outbound portions required to meet associated requirements.

…Unless specifically exempted, the outbound leg of the mission shall meet PP Category IVb requirements. This provision is intended to avoid "false positive" indications in a life-detection and hazard-determination protocol, or in the search for life in the sample after it is returned. A "false positive" could prevent distribution of the sample from containment and could lead to unnecessary increased rigor in the requirements for all later Mars missions.

PP Category IVb requirements read as follows:

Lander systems designed to investigate extant martian life shall comply with all of the requirements of PP Category IVa and also with one of the following requirements:

EITHER
a. The entire landed system is restricted to a surface biological burden level of ≤ 30 spores (see 5.3.2.4 [of NPR8020.12D]) or to levels of biological burden reduction driven by the nature and sensitivity of the particular life-detection experiments, whichever are more stringent, and protected from recontamination.

OR
b. The subsystems which are involved in the acquisition, delivery, and analysis of samples used for life detection are sterilized to these levels. Methods for preventing recontamination of the sterilized subsystems and preventing contamination of the material to be analyzed is provided.

Definition of specific requirements on returnability of the sample cache to meet planetary protection requirements is outside the charter of the SDT, although implementation of such requirements would be a necessary technical step for the mission.

Finding 10-1: In order for a cache to be returnable, it must comply with NASA Planetary Protection requirements in order for future planners to request permission to return it, should they choose to do so.

11 Conclusions

11.1 Summary of High-Level Conclusions Regarding the Proposed Mars 2020 Mission

The Mars 2020 rover as envisioned by the SDT would be the bold next chapter in over two decades of systematic exploration of the nearest, most accessible planet to Earth that may hold a record of past life. Numerous sites on the surface have been found by orbiters to record past, potentially habitable environments in their rock records. *In situ* exploration of an extremely small sample of these environments by MER and MSL confirm past water and potentially habitable conditions. The scientific community has recognized that the next level of exploration of Mars' geologic evolution, past habitability, and the search for signatures of past life requires more sophisticated laboratory measurements, of a level that could only be performed on Earth. Most recently, the Committee on the Planetary Science Decadal Survey (NRC, 2011) recommended that NASA's highest priority for large missions should be one that roves a key site on Mars and assembles a cache of samples for return to those detailed analyses on Earth.

The Mars 2020 SDT has investigated whether, within a constrained cost cap, a mission could take meaningful steps toward this grand objective, while also providing more immediate results by characterizing, *in situ,* past habitability of one site and evidence for biosignatures preservation. The SDT has also considered the potential for the mission to pave the way for future human exploration. We find that these objectives have such a high degree of overlap that they would be most efficiently addressed on a single mission.

For Objective A, *Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability*, the reasoning progressed as:

1. Deciphering and documenting the geology of the rover site requires *in situ*, geological measurements and results from analyzing those measurements.
2. Rover imaging and compositional measurements should be of sufficient coverage, scale and fidelity to permit their placement into the context of the orbital observations that provide the broader spatial coverage required to understand regional geology.
3. A key strategy for interpreting past habitability would be to seek geochemical or geological proxies for past conditions, as recorded in the chemistry, mineralogy, texture, and morphology of rocks.
4. Some aspects of the geological record of past habitable conditions may not be preserved or detectable. **Thus, inability to detect geologic evidence for all four habitability factors (raw materials, energy, water, and favorable environmental conditions) does not preclude interpretation of a site as a past habitable environment.**
5. Five measurement types would be threshold requirements to effectively and efficiently characterize the geology of a site, assess its past habitability, select materials whose laboratory analysis would most significantly advance knowledge of the site's geology and past habitability,

and document the context of samples of those materials: 1) context imaging and 2) context mineralogy, and, within the rover arm's work volume, 3) fine-scale imaging, 4) fine-scale mineralogy, and 5) fine-scale elemental chemistry.

For Objective B, *Assess the biosignature preservation potential within the selected geological environment and search for potential biosignatures*, the following reasoning led to the finding that a returnable cache of scientifically identified and selected materials was needed to accomplish the science objectives:

1. Confidence in interpreting the origin(s) of potential biosignatures increases with the number of potential biosignatures identified, and with a better understanding of the attributes and context of each potential biosignature.
2. **A thorough characterization and definitive discovery of martian biosignatures would require analyses of samples returned to Earth (see Fig. 3-11)**.
3. To investigate the potential for multiple types of biosignatures that might be preserved in multiple geologic units representing both a variety of potential past habitable environments and a range of preservation potentials, at least four or five sample suites must be collected for return to Earth.
4. *In situ* detection of organics would not be required for returning samples to Earth. Other valuable attributes could qualify samples for return, e.g., the presence of other categories of potential biosignatures, or evidence of high preservation potential or a past habitable environment.
5. Six measurement types are threshold requirements to assess biosignature preservation potential and to search for potential biosignatures: 1) context imaging and 2) context mineralogy, 3) fine-scale imaging, 4) fine-scale mineralogy, 5) fine scale elemental chemistry, and 6) organic matter detection. ***Note that the first five threshold measurements are identical with those supporting Objective A, and that here organic matter detection is added.***

Consideration of Objective C, *Demonstrate significant technical progress towards the future return of scientifically selected, well-documented samples to Earth*, produced the following logical progression:

1. The SDT concurs with the detailed technical and scientific arguments made by the Decadal Survey (NRC, 2011) and MEPAG (most recently summarized in E2E-iSAG, 2011) for the critical role returned samples would play in the scientific exploration of Mars.
2. **Significant technical progress by Mars 2020 towards the future return of samples to Earth requires assembly of a cache of scientifically selected, well-documented samples packaged in such a way that the cache could be returned to Earth.**
3. Although there are different ways to organize sample return steps (selection, caching, raising to orbit, return to Earth) into missions, the necessary first step in any scenario is to select and cache samples.
4. **Any progress toward this objective that does not create a returnable cache would have to be repeated in the next mission that makes progress toward sample return. Only through assembly of a returnable cache would that progress not need to be repeated on another mission. A returnable cache retires significant technical risk for sample return, and thus achieves a major milestone worthy of the efforts of spacefaring nations.**
5. The SDT concludes that to achieve Objective C, the threshold science measurements are those listed under Objective A, and the baseline measurements include organic detection as baselined for Objective B.

Objective D, *Provide an opportunity for contributed HEOMD or Space Technology Program participation, compatible with the science payload and within the mission's payload capacity*, inspired the following conclusions:

1. Three classes of environmental measurements are needed to support HEO's long-term objectives: architecturally driven (*in situ* resources, atmospheric measurements for EDL, etc.), safety driven (surface radiation, material toxicity, etc.) and operationally driven (surface hazards, dust properties, electrical properties, etc.).
2. The threshold and baseline measurements that address Objectives A, B, and C also each address various HEOMD strategic knowledge gaps.
3. Returned samples would address the HEOMD objectives related to biohazards, dust properties and toxicity, and regolith chemistry and mineralogy.
4. There are important opportunities for valuable technology development on Mars 2020 that would impact sampling, improved landing site access, planetary protection, improved science productivity, and risk reduction.
5. The CO_2 capture and dust characterization payload is HEOMD's expected contribution to the Mars 2020 mission. By incorporating dust characterization and weather measurements, that payload would also addresses synergistic science objectives.
6. The entry and descent phases of the 2020 mission should be characterized by a system with improvements over the MEDLI system that flew on MSL.
7. The technologies associated with a Range Trigger should be a threshold capability and strongly encourages inclusion of TRN as highest priority baseline so as to help ensure access to high priority sites and reduce science risk related to site selection.

These logical processes led the SDT to reach the following mission-level conclusions regarding the proposed Mars 2020 rover:

1. Significant technical progress by Mars 2020 towards the future return of samples to Earth requires assembly of a cache of scientifically selected, well-documented samples packaged in such a way that they could be returned to Earth.
2. Thorough characterization and definitive discovery of martian biosignatures would require analyses of samples returned to Earth.
3. Five core payload elements – two contextual measurements (imaging and mineralogy) and three types of contact measurements (fine-scale imaging and mineralogy plus elementary chemistry) – together enable thorough analysis of whether the chosen site on Mars was once habitable.
4. Addition of a sixth payload element – to search for preserved organic carbon – enables determination of whether potential biosignatures of past life may exist.
5. These payload elements are the same as those required to select and document the scientifically most important samples for caching. The strategy for collecting and storing samples of key sedimentary, hydrothermal, and igneous rock materials has been described by previous science panels, and we endorse that strategy.
6. The rover platform and the instruments on it address many gaps in the strategic knowledge required for future human exploration of Mars. The rover would also be a suitable platform for key technologies to improve landing accuracy, understand the local environment, and test techniques to extract local resources, that would further prepare not only for human exploration but also for return of the sample cache itself.
7. The mission plan for completing these objectives in one Mars year is ambitious but achievable, if the science instruments are efficient and the plan for exploring the site are chosen carefully.
8. Cost, the technology of caching, and the limitations of even the best robotic instrumentation together prevent creation of a single rover that could both cache as well as produce laboratory-quality sample processing. Caching takes priority because it could lead ultimately to much greater scientific return using Earth-based laboratories.
9. Any Mars 2020 mission that does not create a returnable cache would require any subsequent mission to repeat key aspects in the progress toward sample return. Only the assembly of a returnable cache ensures that these tasks may not need to be repeated on another mission. Only a

returnable cache also retires significant technical risk, and thus would achieve a major milestone worthy of the efforts of spacefaring nations.

The proposed Mars 2020 rover mission is the best, most scientifically impactful next step in exploring the closest world at which humanity might answer the question: Has there been life elsewhere in the solar system?

11.2 Summary of the Strategic Context of the Proposed Mars 2020 Mission

11.2.1 Relationship to the Mars Exploration Program

Beginning in the late 1990s, NASA embarked on a systematic exploration or Mars with astrobiological objectives as one of the elements. This was in part based on the influential 1995 report "An Exobiological Strategy for Mars Exploration". In this report the science foundations for considering Mars as a possible abode of Life were defined along with a long-term, systematic exploration plan was envisioned that would proceed on a rigorous path to assessing if life ever existed on Mars. The strategy was conceptually framed along three corners of a triangle defined by Seek, *In Situ*, and Sample. A sequence of missions was considered that where each would build on the discoveries and knowledge developed by the previous, leading to the selection of samples for return to Earth because it understood that the definitive answers would require the rigor of lab-based measurements. This was not a simple linear path, but one that was responsive to discoveries.

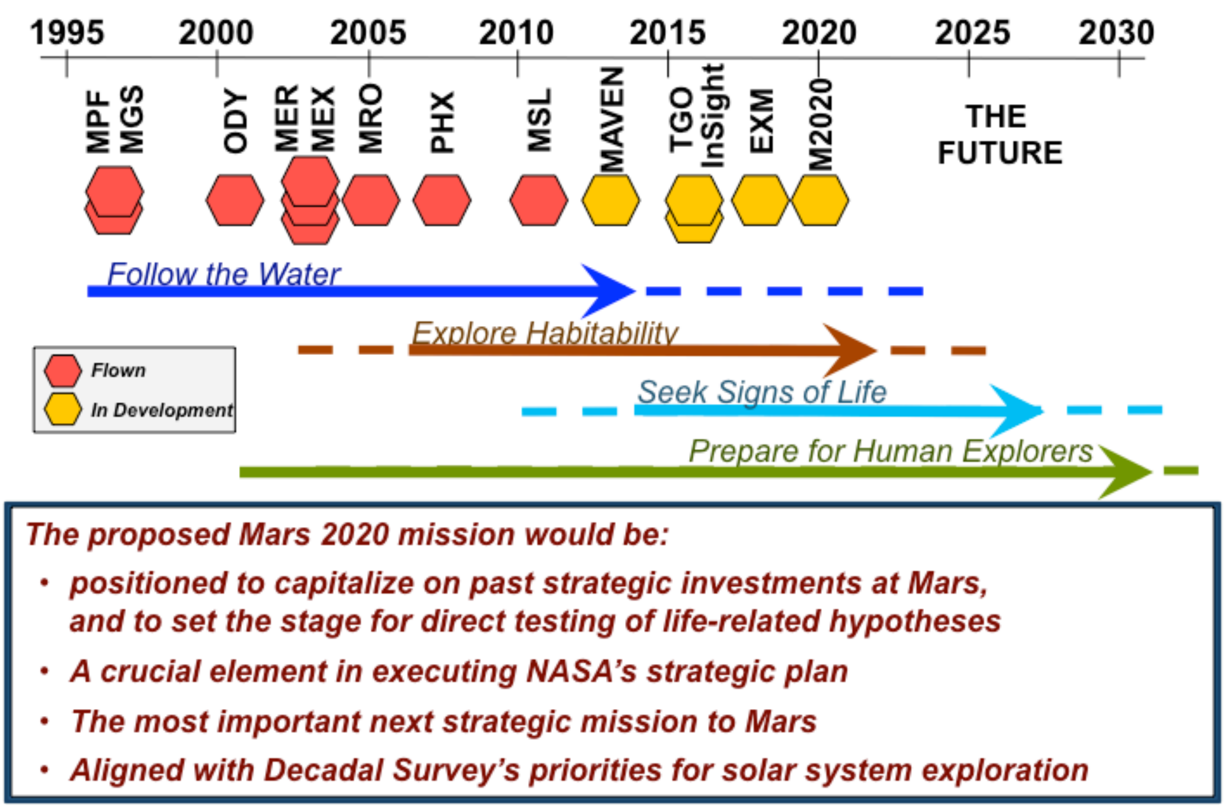


Figure 11-1. Mars has had an integrated Program of exploration following specific goals. *The era of "follow the water" has passed, we are completing "exploring habitability" while "seeking signs of life" is underway.*

Along this path "Seek, *In Situ*, and Sample" the MEP was organized along science themes to focus the measurements and analyses (Fig. 11-1). This was a discovery driven program that was responsive to the ongoing mission and research results. The first framing theme was "Follow the Water" that was extraordinarily successful with the data collected by the Mars Observer, Pathfinder, Odyssey and Mars Exploration Rovers and the seminal contributions by the European Mars Express spacecraft instruments. The theme "Explore Habitability" emerged to take the foundations established with Follow the Water to consider the suitability of environments to support biological activity. The measurements collected by MRO, Mars Express, Phoenix, MER and Curiosity (and that continue to be made) have been central to establishing the scientific foundations of habitability and Curiosity has made some of the most definitive characterizations to date. The missions in development (MAVEN, InSight, ExoMars, and TGO) will continue to make significant advances along this theme.

Progressing from the present state of Mars exploration (recognition of probable habitable environments) to the actual discovery of past or present life requires a coherent, logically organized program of inter-related missions. Many hypotheses have emerged to explain the origin, evolution, and potential for habitability of the classes of aqueous environments recognized from orbit. Landed missions are required to test the hypotheses and address outstanding questions such as the presence and form of fixed nitrogen, the occurrence of reduced carbon, the processes of alteration, and the geochemical characteristics of the possibly habitable environments. NASA's MEP is poised to take the next most important step in the astrobiological strategy for the exploration of Mars: the creation of a returnable cache of carefully selected samples for eventual return to Earth. A mission with this objective would be a key milestone in the new emerging MEP theme, Seeking Signs of Life. Furthermore this would make a significant contribution towards preparing the way for Human explorers.

11.2.2 Summary of what is new/exciting about this mission

As a component of the Mars Exploration Program, the Mars 2020 mission would build on the scientific and technical successes of MER and MSL. Two overarching results from those missions demonstrate that records of past aqueous environments can be recognized from orbital data and rover-based measurements can reveal that such environments were once habitable. Building on MER and MSL, the Mars 2020 rover would apply advanced scientific and engineering capabilities to explore ancient habitable environments and seek signs of ancient martian life (i.e. biosignatures) in ways previously not available. With an improved EDL system and a re-focused payload, the 2020 rover would address the goals of the Mars Exploration Program in two ways: by providing major new *in situ* science results and by initiating the first significant step toward the highly regarded and much anticipated plan to return samples from Mars for detailed study on Earth.

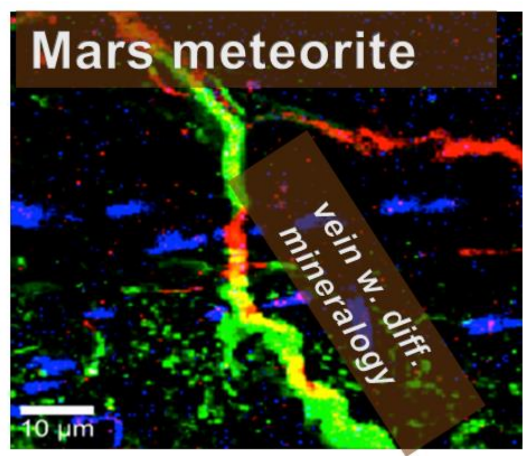


Figure 11-2 Interpreting how rocks were formed and modified is greatly enabled by observing their mineralogy, chemistry, and texture at the scale of the mineral grains. *Shown are green Raman data from a Mars meteorite, Red = jarosite, Green = goethite, Blue = clay minerals. Courtesy M. Fries*

The major advances envisioned for the proposed Mars 2020 mission are as follows:

1. <u>Opening the era of petrology.</u> Previous surface missions all have been capable of measuring the composition of rocks (mineralogy and chemistry, and on MSL also organics and isotopes), but the emphasis has been on measurements that average the composition over an area of several cm^2 or volume of several cm^3 (APXS, Mossbauer, Mini-TES, CheMin, SAM). However, we know from more than a century of careful geologic work on

Earth that observing compositional variations in relation to fine-scale textures and structures provides enormous interpretive power for understanding how rocks were formed and modified: this is the science of petrology (Fig. 11-2). Such observations are especially valuable for interpreting unusual small scale features and patterns in rocks, which is essential to the search for biosignatures. The envisioned 2020 measurement suite would shift away from bulk measurements and instead make higher resolution, spatially coordinated measurements of rock composition, texture and microstructure. These state-of-the-art measurements are the cornerstone of the proposed *in situ* science strategy, and will pave the way to major advances in our understanding of Mars.

2. Improved capabilities for astrobiology. MER and MSL have made critically important observations in the study of Mars' habitability, and MSL can (and will) provide crucial data for understanding Mars' potential to preserve biosignatures. The SAM instrument represents the first implementation of a rover-based capability to measure organic compounds. However, SAM relies on crushed and sieved samples, which destroys important textural information. So although SAM can potentially provide more sensitive measurements with greater information about the composition of the measured substance, we envision a capability for the 2020 mission where spatially resolved measurements in outcrop could:
   - provide observations with sufficient spatial resolution to recognize critical features that occur at the scale of microbial life
   - preserve in detail the all-important context of every measurement
   - detect organics without heating, a drawback in the technique employed by SAM

3. Better access to landing sites. Through improvements to the EDL system, the opportunity to consider scientifically exciting landing sites previously out of reach would open up new possibilities in the search for habitable environments. Many of the sites recognized from orbit to be possible ancient habitable environments are challenging to land on safely with current capabilities. This is why the MSL landing site selection process gravitated toward "go to" sites – MSL could not land directly on some of the most scientifically desirable terrains. The EDL system envisioned for Mars 2020 has the potential to change a large number of them from "go to" to "land on" sites (Fig. 11-3). This is a conceptual change that has huge implications for the kinds of scientific targets that could be reached and explored within the demanding constraints of a rover mission.

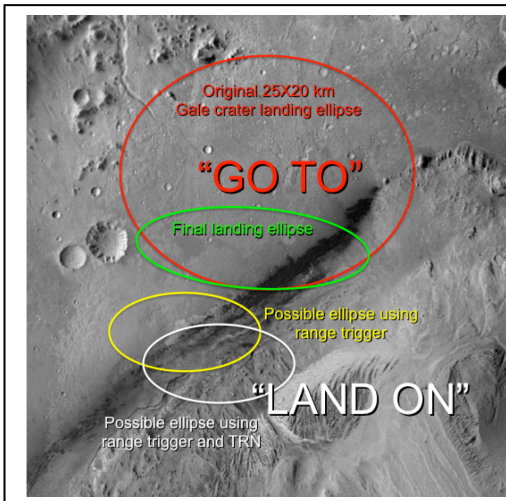


Figure 11-3. Improved EDL technology would allow better access to landing sites by shrinking landing site ellipses and shortening drive distances

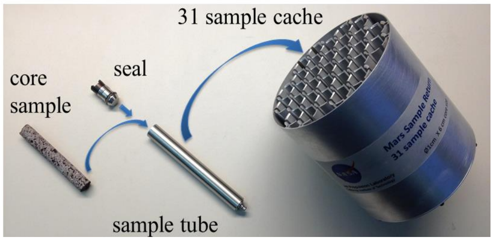


Figure 11-4. "The analysis of carefully selected and well documented samples from a well characterized site on Mars will provide the highest scientific return on investment for understanding Mars" (NRC, 2011). *Courtesy P. Younse.*

4. Sample Caching. The ability to collect and cache scientifically compelling, well-documented samples from *in situ* rock outcrops is unprecedented in Mars exploration and is the necessary first step in a systematic plan to search for life (Fig. 11-4).

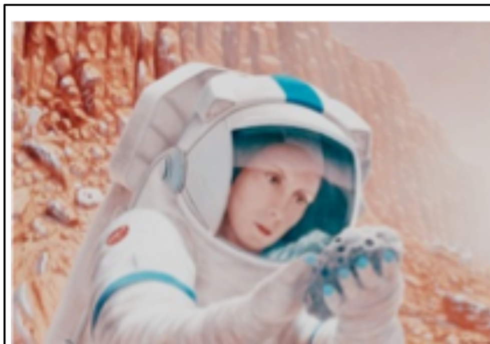


Figure 11-5. Prepare for the future human exploration of Mars

5. Prepare for the Future. Three previous Mars missions have carried investigations specifically designed to collect data to support planning for preparing for the eventual human exploration of Mars (the MARIE instrument on ODY, the MECA experiment on PHX, and the RAD and MEDLI instruments on MSL). Mars 2020 offers the opportunity to extend these preparations in a crucial way (Fig. 11-5).

11.3 Proposed Revised Scientific Objectives for Mars 2020

The charter-specified objectives (Section 2.1) were preliminary statements constructed before the SDT analysis was carried out. The SDT has penetrated these statements in detail over the past 5 months. Given that perspective, if the mission proceeds, the SDT would like to propose a refined set of objectives that better reflects its vision of the mission, and that should flow better into project Level 1 requirements. The intent from the charter (Appendix 1) is that Objectives D and E should be pursued only if compatible with the science payload and if they can be accommodated within the mission's payload capacity.

Summary Statement of Mission Purpose

The Mars 2020 mission would explore a site likely to have been habitable, seek signs of past life, fill a returnable cache with the most compelling samples, take the first steps towards *in situ* resource utilization on Mars, and demonstrate technology needed for the future human and robotic exploration of Mars.

PROPOSED STATEMENT OF OBJECTIVES

A. Characterize the processes that formed and modified the geologic record within a field exploration area on Mars selected as a geologic diverse, astrobiologically relevant ancient environment.

B. Perform the following astrobiologically-relevant investigations on the geologic materials at the landing site:

   1. Determine the characteristics that define the habitability of an ancient environment.

   2. For ancient environments interpreted to have been habitable, determine the biosignature preservation potential.

   3. Search for potential evidence of past life using the observations regarding habitability and preservation as a guide.

C. Assemble a returnable cache of samples for possible future return to Earth.

   1. Obtain samples that are scientifically selected, for which the field context is documented, that contain the most promising samples identified in Objective B, and that represent the geologic diversity of the field site.

   2. Ensure compliance with future needs in the areas of planetary protection and engineering so that the cache could be returned in the future if NASA chooses to do so.

D. Contribute to the preparation for the human exploration of Mars by making significant progress towards filling at least one major Strategic Knowledge Gap [perhaps to be made more specific later].

E. Make a meaningful advancement in the technology needed to enable future strategic Mars missions [perhaps to be made more specific later].

Abbreviated objective statement for use in non-technical applications:

A. Characterize the geology of a site selected for its potential to contain evidence of past habitability as well as for its geologic diversity.
B. Search for possible signs of life preserved in the geologic record.
C. Identify and cache scientifically compelling samples for potential future return to Earth laboratories.
D. Conduct key measurements and demonstrations to enable the possible future human exploration of Mars.

11.4 Proposed Areas for Further Study/ Action

As this report describes the vision of a future mission, there are many items that would benefit from further study.

1. Landing site-related topics

- The SDT proposes that NASA HQ fully fund a landing site selection effort. Most members of the science community do not have specific grants to which they could charge for time on detailed analyses of candidate landing sites or funding to attend landing site workshops. If many early, critical decisions regarding landing site would be needed to influence mission design, a landing site selection process ought to begin early, with appropriate funding.
- The Mars science community should be provided with an early understanding of how the landing site selection process impacts early project decisions regarding EDL technology enhancements and expected surface operations productivity so that appropriate science oversight may be engaged.
- The SDT did not reach final consensus on the required/desired role of igneous rocks at the landing site. The topic of igneous rocks needs community discussion.

2. Planetary protection-related topics. There are several topics of interest for reasons involving issues common to science and planetary protection.
    - Possible Special Regions Issues: What are sites of potential extant life? What is the possibility and implication of deliquescence? Could the science community update the interpretations of the location of sub-surface ice? Should the the quantitative interpretations of water activity made by MEPAG's SR-SAG be revisited?
    - Returned sample issues: What are the considerations relating to the scientific integrity of samples that may potentially be returned to a future user? What are practical approaches to help "preclude" false positive interpretations? What are the options for using science measurements to address PP requirements? If science and planetary protection have fundamentally different proposed requirements in the area of organic contamination, how could these be reconciled?
    - The SDT proposes that future studies and thought be given to agency wide planning for the capability for PP compliance with international regulations, and that technology to enable PP compliance on the 2020 mission be considered in broader context. Resources for PP technology development for application on Mars 2020 would need to be made available almost immediately, lending urgency to these broader considerations.
3. Topics related to improving operational efficiency.
    - The SDT encourages future science and engineering review panels to maintain attention on the critical need to maximize surface productivity and operational efficiency. The SDT has made a number of suggestions for possible ways to improve productivity, but future teams would need to prioritize the options for potential study and implementation.
4. Topics related to the sampling system.
    - Establishing whether each sample tube is full is an issue that is of high value to the SDT. The team feels strongly that the amount of sample in each tube must be well-understood to ensure the scientific value of the cached samples. Previous missions have used a variety of techniques (i.e., the TEGA instrument on the Phoenix Mars Lander, Boynton and Quinn, 2001) to ensure that enough sample has been acquired before continuing an experiment.
    - The issue of blanks and standards requires additional study. MSL chose a series of blanks and included one "spiked" blank. Is that the correct model for Mars 2020? In addition, when should blanks and standards be used in the sample collection chain for Mars 2020?

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14 Appendices

The appendices can be found at:
http://mepag.jpl.nasa.gov/reports/MEP/Mars_2020_SDT_Report_Appendix.pdf