ASTROBIOLOGY
Volume 10, Number 2, 2010
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DOI: 10.1089/ast.2010.0462

The Mars Astrobiology Explorer-Cacher (MAX-C): A Potential Rover Mission for 2018

Final Report of the Mars Mid-Range Rover Science Analysis Group (MRR-SAG) October 14, 2009

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1. Executive Summary

This report documents the work of the Mid-Range Rover Science Analysis Group (MRR-SAG), which was assigned to formulate a concept for a potential rover mission that could be launched to Mars in 2018. Based on programmatic and engineering considerations as of April 2009, our deliberations assumed that the potential mission would use the Mars Science Laboratory (MSL) sky-crane landing system and include a single solar-powered rover. The mission would also have a targeting accuracy of ~7 km (semimajor axis landing ellipse), a mobility range of at least 10 km, and a lifetime on the martian surface of at least 1 Earth year. An additional key consideration, given recently declining budgets and cost growth issues with MSL, is that the proposed rover must have **lower cost and cost risk than**

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those of MSL—this is an essential consideration for the Mars Exploration Program Analysis Group (MEPAG). The MRR-SAG was asked to formulate a mission concept that would address two general objectives: (1) **conduct high-priority *in situ* science** and (2) **make concrete steps toward the potential return of samples to Earth**. The proposed means of achieving these two goals while balancing the trade-offs between them are described here in detail. We propose the name Mars Astrobiology Explorer-Cacher (MAX-C) to reflect the dual purpose of this potential 2018 rover mission.

A key conclusion is that the capabilities needed to carry out compelling, breakthrough science at the martian surface are the same as those needed to select samples for potential sample return to document their context. This leads to a common rover concept with the following attributes:

- Mast- or body-mounted **instruments capable of establishing local geological context** and identifying targets for close-up investigation. This could consist of an optical camera and an instrument to determine mineralogy remotely. Documentation of the field context of the landing site would include mapping outcrops and other accessible rocks, characterization of mineralogy and geochemistry, and interpretation of paleoenvironments.
- A tool to produce a **flat abraded surface** on rock samples.
- A set of arm-mounted instruments capable of **interrogating the abraded surfaces** by creating co-registered two-dimensional maps of visual texture, major element geochemistry, mineralogy, and organic geochemistry. This information would be used to understand the diversity of the samples at the landing site, formulate hypotheses for the origin of that diversity, and seek candidate signs of past life preserved in the geological record. This information could also be used to select an outstanding set of rock core samples for potential return to Earth.
- A **rock core acquisition, encapsulation, and caching system** of the standards specified by the MEPAG Next Decade Science Analysis Group (ND-SAG) (2008). This cache would be left in a position (either on the ground or on the rover) where it could be recovered by a future potential sample return mission.

We propose the following summary primary scientific objectives for the potential MAX-C mission: At a site interpreted to represent high habitability potential with high preservation potential for physical and chemical biosignatures: evaluate paleoenvironmental conditions, characterize the potential for preservation of biotic or prebiotic signatures, and access multiple sequences of geological units in a search for evidence of past life or prebiotic chemistry. Samples necessary to achieve the proposed scientific objectives of the potential future sample return mission should be collected, documented, and packaged in a manner suitable for potential return to Earth.

The scientific value of the MAX-C mission would be significantly improved if it were possible to accommodate a **small secondary payload**. Highest priorities, as judged by this team, are basic atmospheric monitoring, an atmospheric-surface interactions instrument package, and a magnetometer.

The most important contribution of the proposed MAX-C mission to a potential sample return would be the assembly of **a returnable cache of rock core samples**. This cache would place the program on the pathway of a potential 3-element Mars **sample return campaign** [sampling rover mission, combined fetch rover plus Mars Ascent Vehicle (MAV) mission, and orbital retrieval mission]. By preparing a cache, the proposed MAX-C rover would reduce the complexity, payload size, and landed operations time of a potential follow-on mission that would land the potential MAV, thus reducing the overall risk of that follow-on mission. This reduction in mass would facilitate bringing a potential sample return mission's landed mass within heritage (MSL) entry, descent, and landing capabilities. Even though caching would consume mission resources (*e.g.*, money, mass, and surface operation time) that could alternatively be used for *in situ* scientific operations, the benefit to a potential sample return campaign would be compelling.

The proposed MAX-C rover would be **smaller than MSL, but larger than the Mars Exploration Rovers (MERs)**. This makes a reflight of the MSL Cruise/Entry, Descent, and Landing system a prudent cost-effective choice to deliver the proposed MAX-C rover to the surface of Mars. Recent high-level discussions between NASA and ESA have explored the idea of delivering the ESA ExoMars rover and the proposed NASA MAX-C rover to Mars together in 2018 on a single launch and MSL-type Entry, Descent, and Landing (EDL) system. This combined mission concept has been evaluated only briefly thus far. The implementation discussion in this report reflects a proposed NASA-only MAX-C mission, but the general capabilities would not be expected to change significantly for a joint mission architecture.

The proposed MAX-C mission would be launched in May 2018 and arrive at Mars in January 2019 at $L_s = 325^\circ$ (northern mid-winter). Given the favorable atmospheric pressure at this season, performance of the MSL delivery system might allow altitudes up to $+1$ km, but altitude would trade off against the landed mass. There are also unfavorable effects on the atmosphere from an increased probability of dust storms, but the combined effects of these factors have not yet been fully evaluated. Latitude access for a solar-powered rover with a minimum of a 1-Earth-year primary mission lifetime is restricted to between 25°N and 15°S.

The mission concept would require **near-term technology development** in four key areas:

- Coring, encapsulation, and caching: Lightweight tools and mechanisms to obtain and handle cored samples.
- Scientific payload: Instruments capable of achieving the primary scientific objectives need to be matured, particularly for microscale mapping of mineralogy, organic compounds, and elemental composition.
- Planetary protection/contamination control: Methodologies for biocleaning, cataloging of biocontaminants, and transport modeling to ensure cached samples would be returnable.
- Rover navigation: Enhanced onboard image processing and navigation algorithms to increase traverse rate.

As the next lander mission in the Mars Exploration Program, the proposed MAX-C mission would be a logical step in addressing MEPAG's goals, especially for astrobiological and geological objectives. It could be flown alone or with ExoMars and could be sent to a previously visited site or a new more-compelling site selected from orbital data, with sample return objectives included in the site selection criteria. It would be capable of yielding exciting *in situ* mission results in its own right as well as making a significant feed-forward contribution to a potential sample return, and it would likely become the first step in a potential sample return campaign.

2. Introduction

2.1. Background

As noted by MEPAG (2009), Mars has crustal and atmospheric characteristics that make it a priority exploration target for understanding the origins of life. The essential energy, water, and nutrient requirements to support and sustain life are currently present, and the martian geological record offers tantalizing clues of many ancient habitable environments (*e.g.*, Knoll and Grotzinger, 2006; Squyres *et al.*, 2008; Hecht *et al.*, 2009). Recent data from orbiting and landed instruments have been studied by multiple teams of researchers, revealing a complexly dynamic planet with formation of rock units and structures influenced by impact events, crustal melting, tectonism, fluid/rock interactions, weathering, erosion, sedimentation, glaciation, and climate change (see, *e.g.*, Christensen *et al.*, 2003; Neukum *et al.*, 2004; Howard *et al.*, 2005; Tanaka *et al.*, 2005; Bibring *et al.*, 2006; Hahn *et al.*, 2007; Arvidson *et al.*, 2008; Frey, 2008; Murchie *et al.*, 2009; Smith *et al.*, 2009b; Squyres *et al.*, 2009). If life emerged and evolved on early Mars, then it is possible, and indeed likely, that physical or chemical biosignatures are preserved in the exposed rock record. These extraordinary discoveries and inferences make a compelling case for a rover mission designed to explore for evidence of past martian life.

In the 2006 reports of the Mars Advance Planning Group (Beaty *et al.*, 2006; McCleese *et al.*, 2006), a mission concept was introduced that was generically referred to as "Mars mid-rover." This was envisioned as a mission that could be considered for flight in 2016 or 2018, in follow-up to the MSL and ExoMars rovers. The mission concept involved twin "MER-derived rovers directed to different sites to explore the geological diversity on Mars and, perhaps, search for organic material." In February 2008, the MEPAG Mars Strategic Science Assessment Group discussed the possible purpose and value of a single mid-range rover in more detail, given our discoveries at Mars through 2007, and concluded that there could be three significant benefits:

- "Characterization of a new site follows up on discovery of diverse aqueous deposits
- Investigation of each type of deposit promises significant new insights into the history of water on Mars
- Provides additional context for proposed MSR samples"

The MRR concept was also included in the planning work of the Mars Architecture Tiger Team (MATT) (Christensen *et al.*, 2008, 2009). By the time of the MATT-3 report (Christensen *et al.*, 2009), the potential mission was referred to with several different working names, including both Mid-Range Rover and Mars Prospector Rover, and the mission concept was generically envisioned as including a single "MER- or MSL-class rover with precision landing and sampling/caching capability."

- An at least MER-class rover would be deployed to new water-related geological targets.
- Precision landing (<6 km diameter error ellipse) would enable access to new sites.
- The concept would allow investigators to conduct independent science but with scientific and technical feed-forward to Mars Sample Return (MSR).
- As a precursor, this concept should demonstrate feed-forward capabilities for MSR and might open the possibility for payload trade-offs (*e.g.*, caching and cache delivery) with the proposed MSR lander.

Although the strategic importance of a rover mission in about 2016–2018 to Mars exploration was recognized in each of the above planning documents, the specific purpose, rover size, and even the number of rovers was deferred to a future science planning team. For example, none of the above reports penetrated the details of the possible scientific objectives (and the reasons why those objectives are important), how this mission would fit within an evolving programmatic context (most importantly, its relationship to MSL and a possible MSR mission), the investigation strategy, and the preliminary attributes of the rover needed to carry out these objectives. MEPAG has therefore requested an analysis of scientific priorities and engineering implications for this mission concept.

2.2. MRR-SAG Charter

The Mars Exploration Program Analysis Group chartered a Mid-Range Rover Science Analysis Group (MRR-SAG) to analyze

- possible scientific objectives of such a mission,
- the potential contribution of such a mission to the possible future return of samples from Mars, any long-lead technologies that would enable or enhance the potential Mid-Range Rover (MRR) mission and possible subsequent sample return.

The complete charter is provided in MEPAG MRR-SAG (2009).

The MRR-SAG was given the following guidelines for the analysis:

- The MRR mission should include a single solar-powered rover, with a targeting accuracy of 3 km semimajor axis landing ellipse, a rover range of at least 5 km, a lifetime greater than 1 Earth year, and no requirement to visit a Planetary Protection Special region.
- The mission should have two purposes—to conduct high-priority *in situ* science and to prepare for potential sample return.
- Given the forecasted budgetary environment, it is imperative to find mission options that would be lower cost and lower cost-risk than MSL.

After the charter was provided, engineers with expertise in Mars EDL capabilities determined, during the MRR-SAG deliberations, that the targeting accuracy and rover range guidelines needed adjustment. More-realistic capabilities, which were used for the MRR mission concept analyzed in this report, are a semimajor axis landing ellipse of ~ 7 km and a rover range of at least 10 km.

The following specific tasks were assigned:

(1) Evaluate the possible and probable discoveries from MSL and ExoMars that would feed forward to the 2018 (or 2020) opportunity.
(2) Analyze the high-priority *in situ* science that could be accomplished based on Task 1, the MEPAG Goals Document (MEPAG, 2008), and recent National Research Council (NRC) reports. Propose draft statements of the scientific objectives for this mission. Evaluate the kinds of instruments, kinds of landing sites, and nature of surface operations that would be needed to achieve the scientific objectives.
(3) Determine the most important ways (scientific and technical) in which this mission could contribute to a potential sample return.
(4) Analyze the trade-offs associated with simultaneously optimizing Tasks (2) and (3).
(5) Analyze the incremental value to either *in situ* science or potential sample return feed-forward or both, which could be achieved with a modest increase in budget over the baseline assumptions specified above.

As a consequence of feedback from the Mars Architecture Review Team on a presentation of preliminary findings partway through the analysis, and in consultation with the MEPAG Chair and Mars Program administrators, the SAG responded to additional questions with the intent to clarify findings on the above tasks and explore more completely the engineering complexity of a sample cache.

The membership of the MRR-SAG is listed on page 127. Team members were selected by the MEPAG Executive Committee to represent the diversity in expertise within the Mars Program. They have considerable experience in Mars science, in previous and ongoing Mars spacecraft missions, and from membership on MEPAG and other NASA advisory groups. The 27-member team has 6 non-US members, 4 of whom are involved in ExoMars. The team also included three Jet Propulsion Laboratory (JPL) engineers. The SAG also elicited assistance from about 30 other scientists and engineers (see Acknowledgments) in areas where additional expertise was needed.

Right before the MEPAG meeting (July 29–30, 2009), news stories reported the possibility that NASA and ESA might decide to fly a joint mission and send the ExoMars rover and a NASA rover smaller than MSL on the same landing system in 2018. This new scenario would delay the launch of ExoMars from the 2016 launch opportunity to 2018. Because of the timing of this news, a detailed analysis of the option to fly an MRR with ExoMars was beyond the scope of the MRR-SAG. However, even if flown together, the two rovers would probably have different lifetimes and strategies and would eventually end up traversing to different locations. To minimize risk and maximize scientific return, the concept of the MRR as proposed in this report would still be a sensible one, even if flown together with ExoMars. We leave the detailed analysis of this option to future study groups.

To provide a name that fit the mission concept better, the MRR-SAG changed the name of their concept from the generic Mid-Range Rover (MRR) to **Mars Astrobiology Explorer-Cacher (MAX-C)** toward the end of their deliberations in August 2009, and this updated name is used in the rest of this report.

3. Scientific Priorities for a Possible Late-Decade Rover Mission

The Mars Exploration Program Analysis Group actively maintains a prioritized, consensus-based list of four broad scientific objectives that could be achieved with use of the ongoing flight program (MEPAG, 2008):

- Determine whether life ever arose on Mars,
- Understand the processes and history of climate on Mars,
- Determine the evolution of the surface and interior of Mars,
- Prepare for human exploration.

At present, the emphasis of the Mars Exploration Program is on the objective of determining whether life ever arose on the planet. Searching for signs of life on another planetary body requires a detailed understanding of the diversity of life as well as the environmental limits and evolutionary adaptations of life for different physical and chemical settings on Earth. Exploration for life on Mars requires a broad understanding of integrated planetary processes in order to identify those locations where habitable conditions are most likely to exist today or to have existed in the past, and where conditions are, or were, favorable for preservation of the evidence of life if it ever existed. Any endeavor to search for signs of life, therefore, must also seek to understand

- The geological and geophysical evolution of Mars,
- The history of Mars' volatiles and climate,
- The nature of the surface and subsurface environments, now and in the past,
- The temporal and geographic distribution of liquid water,
- The availability of other resources (*e.g.*, energy) necessary for life.

Over most of the last decade, the Mars Exploration Program has pursued a strategy of "follow the water" (formally introduced in 2000; see documentation in MEPAG, 2008). While this strategy has been highly successful in the Mars missions of 1996–2007 (MPF, MGS, ODY, MER, MEX, MRO, and PHX), it is increasingly appreciated that assessing the full astrobiological potential of martian environments requires going beyond the identification of locations where liquid water was present (*e.g.*, Knoll and Grotzinger, 2006; Hoehler, 2007). Thus, to seek signs of past or present life on Mars, it is necessary to characterize more comprehensively the macroscopic and microscopic fabric of sedimentary materials, identify organic molecules, reconstruct the history of mineral formation as an indicator of preservation potential and geochemical environments, and determine specific mineral compositions as indicators of oxidized organic materials or coupled redox reactions characteristic of life. This type of information would be critical to selecting and caching relevant samples in an effort to address the life question in samples intended for study in sophisticated laboratories on Earth.

Two landed Mars missions are currently in development. Although neither has yet returned data, for the purpose of planning, we need to be cognizant of their objectives and possible results. NASA's MSL, scheduled for launch in 2011, has the following objectives (Crisp *et al.,* 2008):

- Assess the biological potential of at least one target environment,
- Characterize the geology and geochemistry of the landing region,
- Investigate planetary processes relevant to past habitability,
- Characterize the broad spectrum of surface radiation.

ExoMars, which ESA plans to launch in 2018, has the following objectives (Vago *et al.*, 2006):

- Search for signs of past and present life on Mars,
- Characterize the water/geochemical distribution as a function of depth in the shallow subsurface,
- Study the surface environment and identify hazards to potential future human missions,
- Investigate the planet's subsurface and deep interior to better understand the evolution and habitability of Mars.

The "Follow the Water" theme has served Mars exploration well by connecting discipline goals in our investigations of Mars just as those processes (geological, geophysical, meteorological, chemical, and potentially biological) have been connected through Mars' history. As the numerous missions to Mars have revealed the diversity of its environments and the complexity of its history, other themes have emerged, which MEPAG has considered and NASA, to some extent, has adopted:

- Introduced in 2000: **Follow the Water** (MGS, ODY, MER, MEX, MRO, PHX)
- Introduced in 2004: **Understand Mars as a System** (All missions)
- Introduced in 2005: **Seek Habitable Environments** (MSL, MSR)

As summarized by MEPAG (2009), the focus of potential missions should be to explore habitable environments of the past and present, including the "how, when, and why" of environmental change. Although quantitatively assessing environmental habitability is the objective of MSL, the growing body of information about the diverse aqueous environments of Mars indicates that we are ready for more ambitious next steps. The NRC (2007) recently concluded, "The search for evidence of past or present life, as well as determination of the planetary context that creates habitable environments, is a compelling primary focus for NASA's Mars Exploration Program." These considerations have led MEPAG to adopt (at the July 2009 MEPAG meeting) "**Seek the Signs of Life**" as its next broad strategy (MEPAG, 2009; Mustard, 2009). There is a drive to have the proposed MAX-C rover mission be the first major mission designed to support this new strategy (see Fig. 3.1).

Sample return from Mars has been advocated by numerous scientific advisory panels for over 30 years, most prominently beginning with the NRC's (1978) strategy for the exploration of the inner Solar System, and most recently by MEPAG's ND-SAG (2008) panel. It remains the highest-priority potential future mission in the Mars Exploration Program. Analysis of samples here on Earth has enormous advantages over *in situ* analyses. Instead of a small, predetermined set of analytic techniques applied to samples analyzed *in situ,* a return of samples would enable the analytical approach to be all-encompassing and flexible. State-of-the-art analytical resources of the entire scientific community could be applied to the samples, and the analytical emphasis could shift as the meaning of each result becomes better appreciated. Sample return has, however, been repeatedly deferred mainly for budgetary reasons.

The possible strategy of using rovers prior to MSR to collect and cache geological samples for possible subsequent return to Earth has been discussed as far back as at least the mid-1990s. The brief mention by Shirley and Haynes (1997) clearly shows that this was being discussed as a conceptual planning option at that time. MacPherson *et al.* (2002) and Steele *et al.* (2005) also briefly discussed sample caching, but particularly noted the potential difficulties of surface rendezvous. These reports were written in the context of MERs that were designed to last for only 90 sols and to travel 600 m (Crisp *et al.,* 2003), so the challenges of physically recovering potential caches appeared quite daunting. The first detailed discussion of caching was presented by MacPherson *et al.* (2005). They pointed out some of the major advantages of caching, including reducing time on the surface for the potential MAV and improving sample documentation by a prior mission that would have more time, and the engineering advantages of sending the potential MSR lander into known terrain. In the Mars Advance Planning Group programmatic planning report (Beaty *et al.,* 2006), sample caching was recognized as a strategy by which to increase the scientific value of a potential future sample return. It would improve the quality of the sample collection returned by a potential MSR by allowing more information to go into sample selection decisions. This was followed up by the NRC (2007), which recommended "sample caching on all surface missions that follow the Mars Science Laboratory, in a way that would prepare for a relatively early return of samples to Earth." In mid-2007, NASA directed that a very simple cache (McKay *et al.,* 2007; Karcz *et al.,* 2008b; design documented by Karcz *et al.,* 2008a) be added to the MSL rover. At the time, MSL was very advanced in its design process, which resulted in a number of significant constraints. Although they endorsed the potential value of sample caching, Steele *et al.* (2008) and the MEPAG ND-SAG (2008) raised serious concerns regarding sample quality for this specific implementation. In November 2008, given the advanced state of MSL's design, it was decided that this cache could not be added without significant consequences in other areas, and the cache was descoped from MSL. Finally, a number of the MSR-related white papers submitted to the 2009 Planetary Decadal Survey discussed the potential strategic importance of MSR-related sample caching, including Borg *et al.* (2009), Farmer *et al.* (2009), Hand *et al.* (2009), Hayati *et al.* (2009), Jakosky *et al.* (2009), MEPAG (2009), Neal *et al.* (2009), and Steele *et al.* (2009).

4. Development of a Spectrum of Possible Mission Concepts

To assess whether the prospective rover mission could meet the scientific goals of the Mars program within the constraints provided, the panel undertook the exercise of

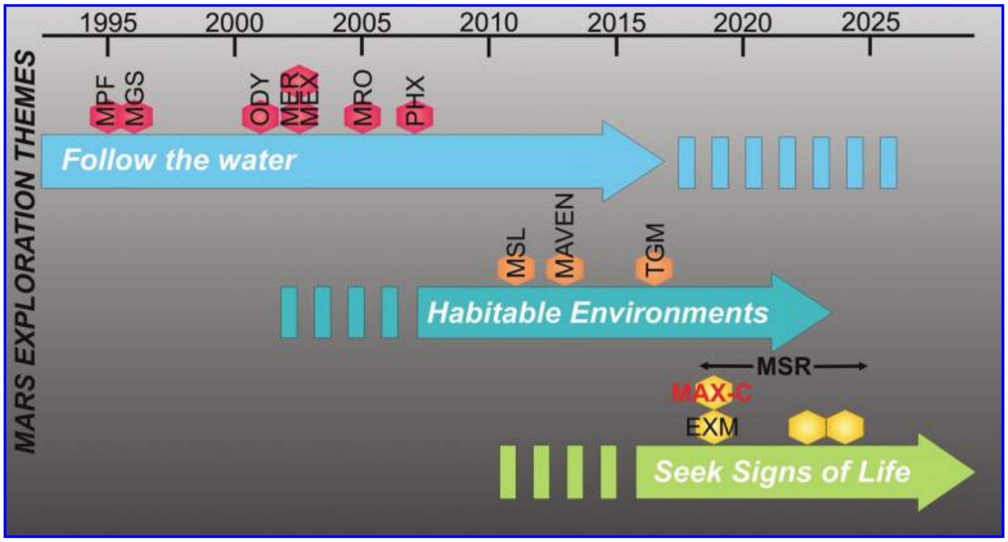

FIG. 3.1. Timeline of launch dates for missions already launched (red), missions in development (orange), and proposed missions (yellow). The proposed MAX-C mission could be the first step in a potential Mars sample return campaign, representing a transition from earlier missions that "followed the water" and missions currently in development that will focus on habitability. Modified after Mustard (2009).

defining and evaluating potential mission scenarios with which to achieve current program priorities and determine the rover capabilities required to accomplish the mission objectives. Building on the long history of scientific exploration on Mars, it is possible to frame a diverse array of highly informed and specific scientific objectives that lay out a path for far-reaching insights to the planet. Many of the key scientific objectives could be addressed with an *in situ* rover mission, and the MRR-SAG committee compiled a list of 28 such objectives that they felt could be addressed by a potential MAX-C mission. Some of the objectives pertain to application of specific types of measurements (or approaches to measurements) that would be valuable for addressing several different scientific questions, whereas others describe the important scientific objectives themselves, without specification of measurements or approaches. Thus, there are many conceptual overlaps and interrelationships within the list. Six broad scientific themes emerged from the list:

- The search for extant life on Mars
- The search for evidence of past life on Mars
- Understanding martian climate history
- Determination of the ages of geological terrains on Mars
- Understanding surface-atmosphere interactions on Mars
- Understanding martian interior processes

The possible scientific objectives and scientific themes could be organized into eight mission concepts (Table 4.1). These mission concepts encompass one or more of the scientific themes listed above. The MEPAG Goals Committee reviewed these mission concepts for completeness and clarity. They pointed out some ways of consolidating the list to make it more useful, which helped to focus in on the definition of the various concepts, but they did not contribute any additional new mission concepts. This helped give us confidence that we had sufficiently covered the full spectrum of high-priority options. SAG members self-selected into eight subgroups (one for each mission concept) that worked to identify fundamental scientific questions, essential information needed, landing site considerations, and mission implementation. These eight mission concepts are described more fully in MEPAG MRR-SAG (2009).

The MRR-SAG also identified several possible augmentations to these missions, which might be accommodated if sufficient funding were available. These augmentations (landed atmospheric science, paleomagnetic measurements, and radiometric dating) are described in Section 5.3 and in more depth in MEPAG MRR-SAG (2009). Note that two of the mission concepts (#3 Radiometric Age Determination and #6 Deep Drilling) could also be considered as augmentations to other mission concepts.

FINDING: Several rover-based mission concepts with compelling scientific objectives have been identified for the 2018 opportunity.

5. Evaluation, Prioritization of Candidate Mission Concepts

5.1. Concept prioritization

The SAG prioritized the candidate mission concepts using the following criteria: scientific value, scientific risk, and breakthrough potential. The priority rankings are given in Table 5.1. Three concepts (reference #4, #2, and #5) clearly ranked higher than the rest. Several mission concepts were determined to be not currently viable, for various reasons. A mission to obtain absolute radiometric ages for surface materials (Concept #3) was considered to offer potential future promise, but technologies that allow age determinations *in situ* appear not yet to be mature or cost effective (*e.g.*, Conrad *et al.*, 2009). A mission to investigate methane seeps (Concept #7) had strong astrobiological interest, but the SAG did not see a clear path that would provide sufficient information on the spatial

TABLE 4.1. MISSION CONCEPTS AND PROPOSED PRIMARY OBJECTIVES

Ref #	*Mission concept*	*Primary scientific objectives*
1	Mid-latitude ice analysis	Characterize periglacial sites for habitability, evaluate *in situ* resource potential of shallow ice deposits (similar to Phoenix, but mid-latitude).
2	Noachian-Hesperian boundary	Understand environmental change across this important boundary, define its age, explore implications of boundary for habitability and biosignature preservation potential.
3	Radiometric dating	Determine absolute ages of a stratigraphic sequence relevant to astrobiology—in support of another concept or to provide calibration for crater retention.
4	Mission to Early Noachian terrain	Address questions about early Mars history, possible transition from prebiotic to biotic chemistry and primitive cells, potential biological evolution in relation to changes in the magnetic field, atmosphere, and impact rate.
5	Astrobiology new terrain	Search for evidence of life and habitability in an astrobiologically significant terrain type that has not yet been explored.
6	Deep drilling (~2 m)	Understand surface oxidation and its effect on carbon and life. (Overlaps with ExoMars goals.)
7	Methane seep	Analyze methane and reduced gases emitted from the subsurface and assess their possible connection to life.
8	Traverse and analyze polar layered deposits	Assess global climate change and secular evolution of water.

Note: numbers are the SAG's reference numbers only, and do not indicate rankings.

distribution of such seeps to allow targeting for the 2018 launch opportunity, even with a potential Trace Gas Mapper in 2016 (Smith *et al.*, 2009a). This could be revisited later if a Trace Gas Mapper is selected, and after its capabilities have been defined. A potential mission to polar layered deposits (Concept #8) was not considered viable because the SAG was informed that it appears there are no reasonably achievable trajectories to high-latitude sites in the 2018 launch opportunity. Moreover, a rover mission trying to last a year would have a severe power challenge at such high latitude. In addition to the rankings, members of the team were invited to add comments that explained the reasons behind their rankings. These comments were compiled by concept and, within each concept, organized into positive and negative remarks. A summary of the more notable points that were raised is given in MEPAG MRR-SAG (2009).

The MRR-SAG team had a mixture of scientific expertise that could be broadly grouped into three categories: geologists, astrobiologists, and atmospheric scientists plus geophysicists. Because perspective on relative priority for concepts as diverse as these can be quite dependent on discipline balance, we show in Table 5.2 the relative priorities of the eight mission concepts as judged by these three discipline groups. Most importantly, Concepts #2 and #4 were rated the top two priorities by each of the three discipline groups, and Concept #5 was rated a third priority by two of the groups and fourth by the other. The differences between these groups were that the atmospheric scientists saw higher value in Concept #1 (relating to mid-latitude ice), the astrobiologists saw higher value in Concept #7 (methane), and the geologists saw higher value in Concept #3 (age dating). However, the convergence of all sectors of the team on Concepts #2, #4, and #5 is an important foundation for formulating a consensus mission concept.

5.2. Integration into a single mission concept

It is increasingly appreciated that assessing the full astrobiological potential of martian environments requires going beyond the identification of locations where liquid water is,

TABLE 5.1. SCIENTIFIC PRIORITIZATION OF THE EIGHT MISSION CONCEPTS

		PRIORITY			
Concept #	*Mission Concept*	*Science value*	*Science risk*	*Breakthrough potential*	*OVERALL*
4	Astrobiology Mission to Early Noachian Mars	2.7	2.3	2.6	2.5
2	Stratigraphic Sequence near Noachian-Hesperian Boundary	2.6	2.2	2.5	2.4
5	Astrobiology: New Terrain	2.5	2.1	2.4	2.3
7	Detection of Methane Emission from the Martian Subsurface	2.3	1.2	2.5	2.1
3	Radiometric Dating	2.3	1.5	2.1	1.9
6	"Deep" Drilling	1.9	1.6	1.9	1.8
8	Polar Layered Deposits Traverse	1.8	1.7	1.7	1.7
1	Mid-Latitude Shallow Ice	1.7	1.9	1.7	1.5

MRR-SAG members scored each concept from 1 (low value, high risk, low breakthrough potential) to 3 (high value, low risk, high breakthrough potential). Average scores of the MRR-SAG votes are listed above. Green boxes highlight the averaged scores >2.5.

Table 5.2. Top Four Mission Concepts (Indicated by Reference Numbers) in Overall Science Priority, by MRR-SAG Member Primary Discipline

Overall Science Priority	Geologists (12 voting)	Astrobiologists (8 voting)	Atmospheric Scientists and Geophysicists (3 voting)
1	#4	#4	#2
2	#2	#2	#4
3	#3	#5	#5
4	#5	#7	#1

or was, present (*e.g.,* Knoll and Grotzinger, 2006). Thus, to seek signs of past or present life on Mars, basic requirements include more comprehensive characterization of the macroscopic and microscopic fabric of sedimentary materials, detection of organic molecules, reconstruction of the history of mineral formation as an indicator of preservation potential and geochemical environments, and determination of specific mineral compositions as indicators of oxidized organic materials or coupled redox reactions characteristic of life. This essential science lies at the heart of each of the top three candidate mission concepts: #2, #4, and #5. Example landing sites for these concepts are shown in Fig. 5.1.

This leads us to conclude that a single rover with the same general capabilities could be used to explore a wide range of landing sites of relevance to all three of the candidate missions. Each of these three candidate mission concepts relates to astrobiology, and all entail understanding paleoenvironmental conditions. Understanding preservation potential would be important for all three candidate mission concepts, and all are of interest for assessing possible evidence of past life or prebiotic chemistry. A single general mission implementation would allow the Mars Exploration Program to respond to discoveries over the next several years in any of the above areas with the distinction between these scenarios resolved in a landing site competition.

MAJOR FINDING: A single rover with the same general capabilities and high-level scientific objectives could explore one of a wide range of landing sites relevant to the top three mission concepts. The differences between the concepts primarily relate to where the rover would be sent, rather than how it would be designed.

It is possible to frame a single statement of scientific objective (see below) that encompasses all three of these mission concepts. First, since one of the Mars Exploration Program's current strategies is to evaluate differences in habitability potential as a function of both space and time, it is presumed that sites with comparatively high potential will have been identified as input to both mission planning and site selection. This is a crucial prioritization strategy that would allow the proposed MAX-C rover to be inserted into an environment with high scientific potential. Second, each of the high-priority mission concepts relates to ancient environments on Mars rather than modern environments. Thus, the scientific objectives relate to the kinds of things investigators would want to do in such an environment, which include evaluating paleoenvironmental conditions, characterizing the potential for the preservation of biotic or prebiotic signatures, and accessing multiple sequences of geological units in a search for possible evidence of ancient life or prebiotic chemistry.

PROPOSED PRIMARY *IN SITU* SCIENTIFIC OBJECTIVES:
At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:

- **evaluate paleoenvironmental conditions,**
- **characterize the potential for the preservation of biotic or prebiotic signatures, and**
- **access multiple sequences of geological units in a search for possible evidence of ancient life or prebiotic chemistry.**

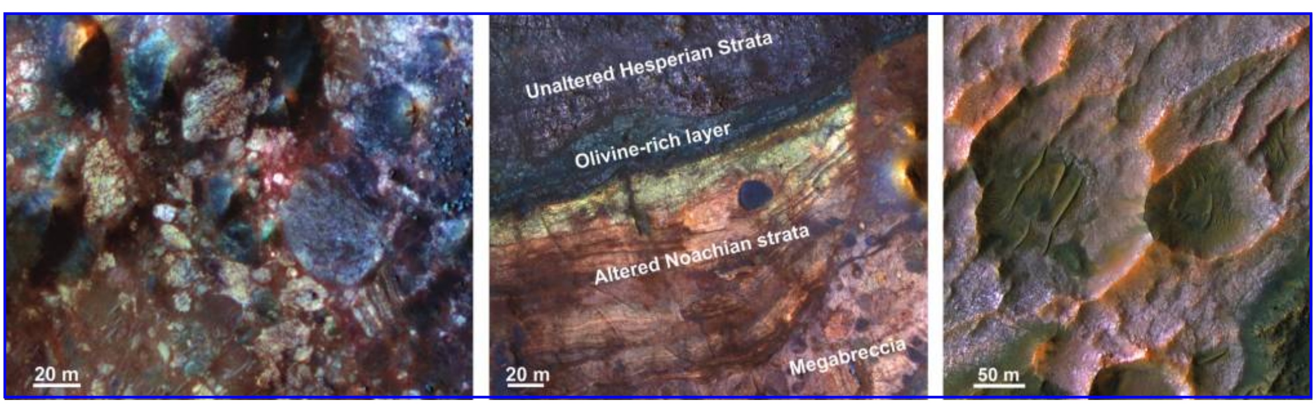

FIG. 5.1. (Left) Example of a location that might be suitable for Mission Concept #4 (Early Noachian Astrobiology): megabreccia with diverse lithologies in the watershed of Jezero Crater. Subframe of a HiRISE color image PSP_006923_1995. (Center) Example of a location that might be suitable for Mission Concept #2 (Stratigraphic Sequence at the Noachian-Hesperian Boundary): stratigraphy of phyllosilicate-bearing strata in the Nili Fossae region, where CRISM detected phyllosilicates in the Noachian strata and megabreccia. Subframe of a HiRISE image PSP_002176_2025. (Right) Example of a location that might be suitable for Mission Concept #5 (Astrobiology–New Terrain): potential chloride-bearing materials in Terra Sirenum. Subframe of a HiRISE image PSP_003160_1410. Credit for all three images: NASA/JPL-Caltech/University of Arizona.

5.3. The possibility of one or more secondary scientific objectives

At this stage of planning, it is not clear what the final resource constraints on a possible next-decade rover mission would be. For this reason, it is important to consider the possibility of secondary scientific objectives, for which it may ultimately be possible to fit necessary instruments within the mission's resource limitations. A number of ideas were raised during the course of the team's deliberations. On the basis of its collective sense of current scientific priorities and engineering/financial feasibility, the MRR-SAG recognized two broad classes of investigation that appear to be particularly good candidates for the potential MAX-C mission, which relate to landed atmospheric science and paleomagnetic studies. In both cases, additional expertise was solicited to document the possible scientific objectives and possible implementation strategies—these amplified analyses are presented in MEPAG MRR-SAG (2009).

Landed atmospheric science. An important scientific objective related to landed atmospheric science would be to determine the relationships that govern surface/atmosphere interaction through exchange of volatiles (including trace gases), sediment transport, and small-scale atmospheric flows, all of which are necessary to characterize Mars' present climate. Measurement of wind velocities, surface and air temperatures, relative humidity, dust emission (either through saltation impact or otherwise), air pressure, and trace gas fluxes are all necessary to determine the relationships that control surface/atmosphere interactions. To characterize the exchange of momentum, heat, volatiles, and sediment between the surface and atmosphere, it would be necessary to have a dedicated suite of instruments that functions for extended periods of time and obtains precise measurements of high frequency so that subsecond, hourly, diurnal, seasonal, and interannual variations are resolved and monitored (Rafkin *et al.*, 2009). With the current lack of martian observations, empirical relations acquired on Earth are typically applied to estimate fluxes between the martian surface and atmosphere, with unknown errors. Thus, these data would be essential for understanding the current climatic state of Mars, determining potential sources of trace gases that might lead to the discovery of life, and constraining atmospheric models that are needed to ensure safe landing conditions for potential future spacecraft.

Within MEPAG MRR-SAG (2009), draft priorities within a multiple set of possible landed atmospheric scientific investigations are described, which could determine the relationships that govern surface/atmosphere interaction through exchange of volatiles (including trace gases), sediment transport, and small-scale atmospheric flows. Of everything in the list, the most important is judged to be measurement of the atmospheric pressure, which is the "heartbeat" of the atmospheric system (Rafkin *et al.*, 2009) and would provide a measure of the total atmospheric mass, which is related to formation and sublimation of the polar ice caps (Titus *et al.*, 2009).

Paleomagnetic studies. Objectives for paleomagnetic investigations are described in detail in MEPAG MRR-SAG (2009) and are also advocated in the Decadal Survey white paper by Lillis *et al.* (2009). Mars presently does not have a core dynamo magnetic field, but the discoveries of intense magnetic anomalies in the ancient southern cratered terrane by the Mars Global Surveyor mission (Acuña *et al.*, 1998) and remanent magnetization in martian meteorite ALH 84001 (Kirschvink *et al.*, 1997; Weiss *et al.*, 2002) provide strong evidence for a martian dynamo active during the Noachian epoch. The time of origin and decay of this global field is poorly constrained but has critical implications for planetary thermal evolution (Stevenson, 2001), the possibility of an early giant impact (Roberts *et al.*, 2009), the possibility of early plate tectonics (Nimmo and Stevenson, 2000), and the evolution of the martian atmosphere and climate (Jakosky and Phillips, 2001). Paleomagnetic studies have yielded two pieces of information: the intensity and the direction of ancient fields. Because the original stratigraphic orientations of martian meteorites are unknown, all Mars paleomagnetic studies, to date, have only been able to measure the paleointensity of the martian field (Weiss *et al.*, 2008). In situ *paleomagnetic studies from a Mars rover would provide unprecedented geological context and the first paleodirectional information on martian fields.* The data could be used to address at least four very important scientific questions:

(1) When was the martian magnetic field present, and when did it disappear? Did the death of the martian dynamo lead to atmospheric loss and climate change?
(2) Did ancient magnetic fields definitely arise from a core dynamo?
(3) How did the martian paleofield vary in time? Did it experience reversals and secular variation, and if so what were their frequencies?
(4) Did Mars experience plate tectonics or true polar wander?

Unlike landed atmospheric science packages (which have flown on missions, including Viking and Pathfinder, and will also be on the upcoming MSL mission), a paleomagnetism package has never been flown on any martian lander.

Other possible secondary objectives considered included a geochronology experiment, a seismic investigation, and scientific objectives related to drill acquisition of subsurface samples. The judgment of the SAG was that, though there are very strong scientific reasons for these investigations, they are of a character that would be more appropriate as the primary objective of a separate mission, not as a secondary objective squeezed into a mission that has an alternate primary purpose. If the resource parameters of the mission change significantly in the future, these possibilities should certainly be reconsidered.

Balancing all the above possibilities with the realities of limitations on mass and money, the SAG concludes that *at least* one secondary payload should be accommodated and that the single highest priority is an atmospheric pressure sensor.

FINDING: Inclusion of at least one secondary scientific objective would substantially enhance the scientific return of the proposed mission. The single highest priority would be to monitor the atmospheric pressure as a function of time at the martian surface.

6. Strategy to Achieve Primary *In Situ* Objectives

If rocks and outcrops are limited in extent within the landing ellipse (which may be a necessary condition to ensure safe landing), the important process of quickly constraining geological setting, selecting sample locations, and providing context for samples might be challenging. Indeed, the MER experience shows that considerable time would be spent locating outcrops and evaluating them upon arrival. These considerations lead to the following finding:

FINDING: The proposed MAX-C mission must have the capability to define geological setting and remotely measure mineralogy in order to identify targets for detailed interrogation by the arm-mounted tools from a population of candidates and place them in stratigraphic context.

In addition, interpretation of the geological setting and placement of observations in stratigraphic context could be significantly enhanced by subsurface sensing, such as ground-penetrating radar or seismic profiling (although the latter is unlikely to be feasible). The potential MAX-C traverse capability would affect the specific requirements for remote sensing (resolution, downlink volume). Orbital data would be very useful for strategic traverse planning but not sufficient for tactical planning.

Implementation of the proposed MAX-C mission objectives would require interpretation of the origin and subsequent modification of rocks with as-yet unknown mineral composition, macroscale structure, and degree of heterogeneity. Given these unknowns, it is challenging to identify the specific set of measurements that would be required in the future by such a rover mission. However, relevant experience from study of ancient terrestrial strata, martian meteorites, and from MER indicates that the proposed rover's interpretive capability should include

- Mineralogical remote sensing at ~ 1 mrad/pixel or better, signal-to-noise ratio (S/N) >100;
- Geomorphological context (optical) imaging at ~ 0.3 mrad/pixel or better;
- Abrasion of ~ 3 cm diameter areas on rocks;
- Measurements of the abraded rock surfaces:
  - Optical texture at $\sim 30\,\mu$m/pixel resolution or better, $S/N > 100$,
  - Mineralogical two-dimensional mapping with ~ 0.3 mm spatial resolution, $S/N > 100$,
  - Organic detector two-dimensional mapping with ~ 0.1 mm spatial sampling,
  - Elemental chemistry two-dimensional mapping with ~ 0.1 mm spatial resolution (if not possible to accommodate, then bulk chemical composition measured on a few cm diameter spot).

For three primary reasons, we propose that the measurement strategy focus on interrogation of abraded surfaces: (1) We know from the results of MER that a variety of microscopic textures are present on Mars (see Fig. 6.1); (2) We know that surface analysis techniques have significantly lower cost and risk in comparison to acquiring rock chips or powders (comparative experience from MER and MSL); and (3) A number of suitable instruments are either already developed or under development in each of these four areas identified (see Section 6.1). This class of instruments makes use of a relatively smooth, abraded rock surface, such as is produced by the Rock Abrasion Tool (RAT) grinder on MER (Gorevan *et al.*, 2003). Note that this strategy and the mission objectives would require access to outcrops, a consideration that has implications for the landing site attributes.

FINDING: Outcrop access is fundamental to the MRR mission concept. This has implications for landing site selection.

For measurements of mineralogy and chemistry, instruments used to interrogate smoothed rock surfaces directly

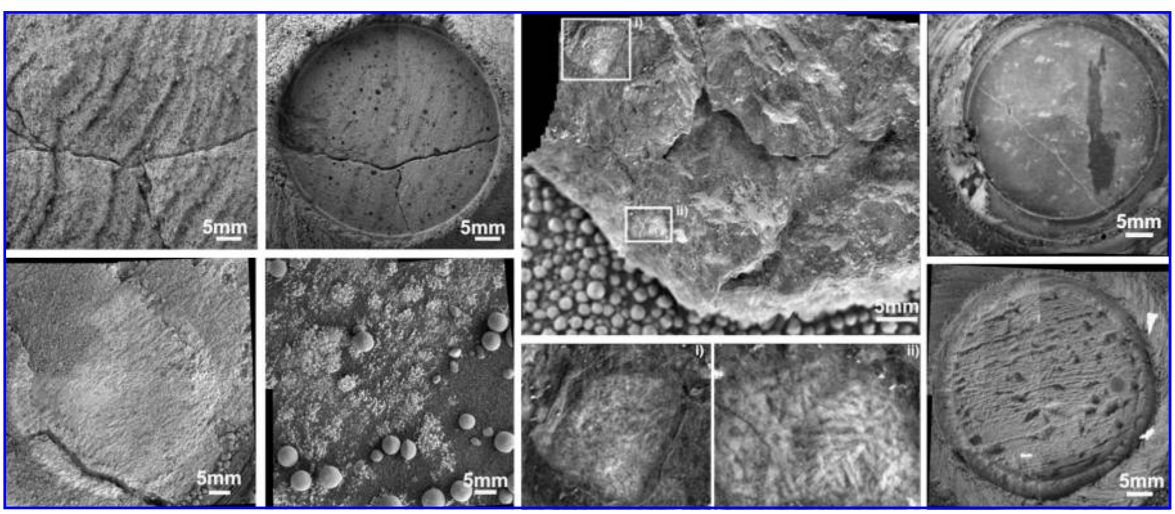

FIG. 6.1. MER close-up visual examination has revealed interesting textures on relatively smooth rock surfaces of martian rocks, as shown in these example images. Credit: NASA/JPL-Caltech/USGS. Detailed results from the MER Microscopic Imager investigations are described in Herkenhoff *et al.* (2004, 2006, 2008). Micro-mapping could be used to study origins of minerals, depositional/formation sequences, presence and duration of liquid water, and the presence and nature of any organic deposits or biominerals.

typically cannot match the analytical accuracy and precision attained by instruments that ingest samples. However, the data quality would be sufficient to meet key scientific objectives, and the ability of such instruments to characterize intact outcrops would offer substantial advantages. Although in the past we have used instruments that average the analytic data over an area at least centimeters in size (*e.g.*, Christensen *et al.*, 2004; Clark *et al.*, 2005; McLennan *et al.*, 2005; Squyres and Knoll, 2005; Arvidson *et al.*, 2006; Gellert *et al.*, 2006; Glotch *et al.*, 2006; Morris *et al.*, 2006a, 2006b, 2008; Squyres *et al.*, 2006), spatial resolution down to scales of tens of micrometers is readily achievable with newer instrumentation (see Section 6.1). Some instruments can produce data in a two-dimensional scanning mode, which would be exceptionally powerful. If observations of texture, mineral identification, major element content, and organic materials are spatially co-registered, they can interact synergistically to strengthen the ultimate interpretations. This two-dimensional micro-mapping approach is judged to have particularly high value for evaluating potential signs of ancient microbial life, key aspects of which are likely to be manifested at a relatively small scale. We conclude that the two-dimensional micro-mapping investigation approach is an excellent complement to the data anticipated from MSL, which will have higher analytical precision but lower spatial resolution.

In MEPAG MRR-SAG (2009), a more detailed description of the proposed "science floor" replaces two-dimensional elemental mapping with bulk elemental analysis on a 1.5–2.5 cm diameter spot, relaxes the recommended required resolution of the mineralogical remote sensing and visible imaging, and relaxes the recommended required spatial resolution of *in situ* mineralogical mapping and organic compound measurements.

The panel concluded that recommendation of specific instruments to accomplish the recommended required measurements should be left to a future Science Definition Team but recognized the need for a straw-man payload to support engineering trade studies and mission planning. We have carefully evaluated the available means of collecting these kinds of data without acquisition of rock chips or powders and have learned that a number of suitable instruments are either already developed or under development (at least Technology Readiness Level-3) in each of these four areas identified. This class of instruments makes use of a relatively smooth, abraded rock surface, such as is produced by the RAT on MER. We expect there to be some dependency of the accuracy and precision of measurement results on the physical character of the abraded surface. Some kinds of measurements of surfaces are affected by surface roughness, flatness, and so on. Setting specific requirements in this area would need further study by a successor team.

6.1. Some classes of instruments relevant to primary in situ *objectives*

The MRR-SAG arranged for a survey of the status and capabilities of various remote sensing and *in situ* instruments that could meet the proposed MAX-C objectives (credit to Dr. Sabrina Feldman, JPL). We found that there are a number of potentially important instruments that could meet the recommended measurement requirements of the proposed mission that currently have a Technology Readiness Level (TRL) of at least TRL-3, though only a fraction are as advanced as TRL-6 (the state of readiness needed by the time of mission Preliminary Design Review). Continuing development of these instruments would be very important in supporting a good instrument competition in response to an Announcement of Opportunity for the proposed MAX-C mission.

FINDING: There are a number of potentially useful instruments that could meet the measurement requirements of the proposed mission that currently have a Technology Readiness Level (TRL) of at least TRL-3.

Some examples of these instruments that could be flown on the proposed MAX-C mission are described below. The purpose is not to advocate that these particular instruments should be a part of the proposed mission. Rather, these descriptions could be used by scientists to consider the full scientific potential of this sort of mission and by engineers to check the feasibility of accommodating an instrument suite that could meet the recommended measurement objectives formulated in this report.

6.1.1. Multispectral Microscopic Imager (robotic arm–mounted). Microimaging capability—in the form of a geologist's hand lens—has long been an essential tool for terrestrial field geology. Imagery at the hand-lens scale (several cm field of view resolved to several tens of microns) provided by the Microscopic Imagers on the MERs and the Robotic Arm Camera (Keller *et al.*, 2008) on the Phoenix lander has proven so vital to the success of these missions and to the Mars Exploration Program (Herkenhoff *et al.*, 2004, 2006, 2008) that a microimager is one of the two instruments now recognized as essential for Mars surface missions (MEPAG ND-SAG, 2008). The microtextures of rocks and soils, defined as the microspatial interrelationships between constituent mineral grains, pore spaces, and secondary (authigenic) phases (*e.g.*, cements) of minerals, provide essential data for inferring both primary formational processes and secondary (postformational) diagenetic processes. Such observations are fundamental for properly identifying rocks, interpreting the paleoenvironmental conditions they represent, and assessing the potential for past or present habitability. Multispectral, visible-to-near-infrared microimages could provide context information for evaluating the spatial (and implied temporal) relationships between constituent mineral phases characterized by other mineralogical methods that lack context information. Microimaging could also provide highly desirable contextual information for guiding the subsampling of rocks for potential caching or additional analyses with other *in situ* instruments. Figure 6.2 shows 3-band-color-composite images, both natural color and false color, composed of bands selected and extracted from a 21-band visible/near-infrared image set acquired by the Multispectral Microscopic Imager (Sellar *et al.*, 2007; Nuñez *et al.*, 2009a, 2009b).

The images reveal important information about the depositional processes that formed this volcaniclastic sedimentary rock and also about the microscale aqueous

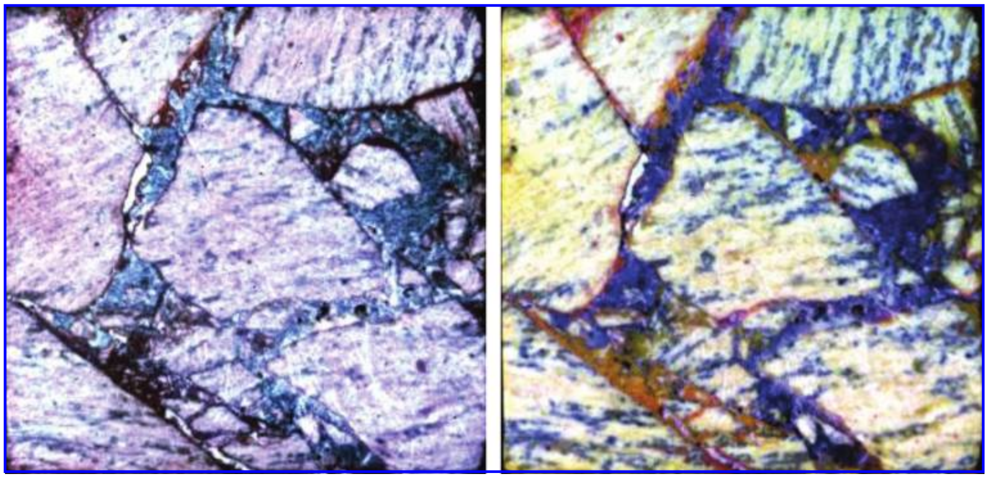

FIG. 6.2. Natural-color image (left) composed of 660, 525, and 470 nm bands; and false-color image (right) composed of 1450, 1200, and 880 nm bands; displayed in red, green, and blue, respectively; selected subframe shown here is 20×20 mm (full field is 40×32 mm) with a resolution of 62.5 μm/pixel. This sample was ground to a roughness similar to that provided by the RATs on the MERs. Interpretation: volcanic breccia. Angular clasts of a fine-grained silicic volcanic rock have been cemented by calcite and hematite. Angular shapes and poor size sorting of clasts indicate minimal transport. This, along with the uniformity of clast compositions (monolithologic), suggests deposition near the volcanic source, perhaps as an airfall tuff (lapillistone).

environments that existed within the rock during its early postburial history. The Multispectral Microscopic Imager is estimated to have a mass of about 1.6 kg and consume ~19 W peak including electronics.

6.1.2. XRF Chemical Micro-Mapper (robotic arm–mounted). X-Ray fluorescence (XRF) chemical micro-mapping produces a series of high-resolution element maps that show the spatial distribution of chemical elements in rocks. These hand-lens scale maps can be digitally overlaid to reveal covariations between elements and relationships between chemical composition and visible textures and microstructures. This information can be used to

- Determine the mineral composition of individual grains, cements, alteration rims, fracture-fills, and so on;
- Detect otherwise cryptic features such as textural components that have the same mineralogy, but slightly different elemental composition;
- Verify mineralogical interpretations and identify mineral types that can be difficult to constrain with other spectral techniques.

X-Ray fluorescence micro-mapping is inspired by state-of-the-art benchtop chemical mapping instruments. These instruments use a capillary optic (Ohzawa, 2008) to focus an X-ray beam down to a 100 μm spot. The beam is raster scanned across the sample surface, while XRF spectra are rapidly acquired at close spacing, which gradually builds up a raster image for each element measured (*e.g.,* Fig. 6.3). Up to 14 single-element maps are acquired simultaneously, detecting elements from Na to U, over a map size of up to 10 cm×10 cm.

The flight instrument would also consist of a capillary focusing optic, miniature X-ray tube, detector array, and two-dimensional translation stage (all mounted on the arm) operated with a high-voltage power supply and detector electronics (mounted in the rover body and connected via insulated cable along the rover's robotic arm). The estimated total mass of a flight X-Ray Micro-Mapper is ~2.5 kg, with power consumption of ~30 W. Preliminary estimates suggest that the X-Ray Micro-Mapper could analyze a 1 cm^2 area of an abraded rock surface on Mars at 100 μm resolution in about 3 hours.

The scientific value of the technique has been validated through studies of ~3.5 billion-year-old rocks containing the oldest evidence of life on Earth: element maps acquired with a commercial X-ray guide tube X-ray analytical microscope have revealed mineralogy and key aspects of rock fabrics that constrained paleoenvironmental conditions, habitability, and biogenicity in Early Archean stromatolites (Fig. 6.3) (Allwood *et al.,* 2009). In the context of planetary exploration, chemical mapping would have even greater value and provide a valuable substitute for thin section petrography (a fundamental part of geological studies on Earth, but complex and resource intensive for robotic planetary exploration). Using XRF to map covariations among elements against a backdrop of optical imagery would achieve many key objectives of thin section petrography.

6.1.3. Alpha particle X-ray elemental chemistry instrument (robotic arm–mounted). An alternative to the XRF Chemical Micro-Mapper (Section 6.1.2) is provided by an alpha particle X-ray spectrometer (APXS). An APXS provides bulk chemical analysis averaged over an area a few cm in diameter. The advantages of the APXS include flight heritage, fast analyses, and small data size.

An APXS similar to the one built for MSL could provide bulk elemental composition measurements (Na to Br) on rock or soil surface target areas ~1.7 cm in diameter, to a depth of 5–50 μm. The MSL APXS has significant heritage from the APXS instruments flown on Spirit and Opportunity (Rieder *et al.,* 2003; Gellert *et al.,* 2006, 2009). A thermoelectric cooler allows operation up to martian ambient temperatures

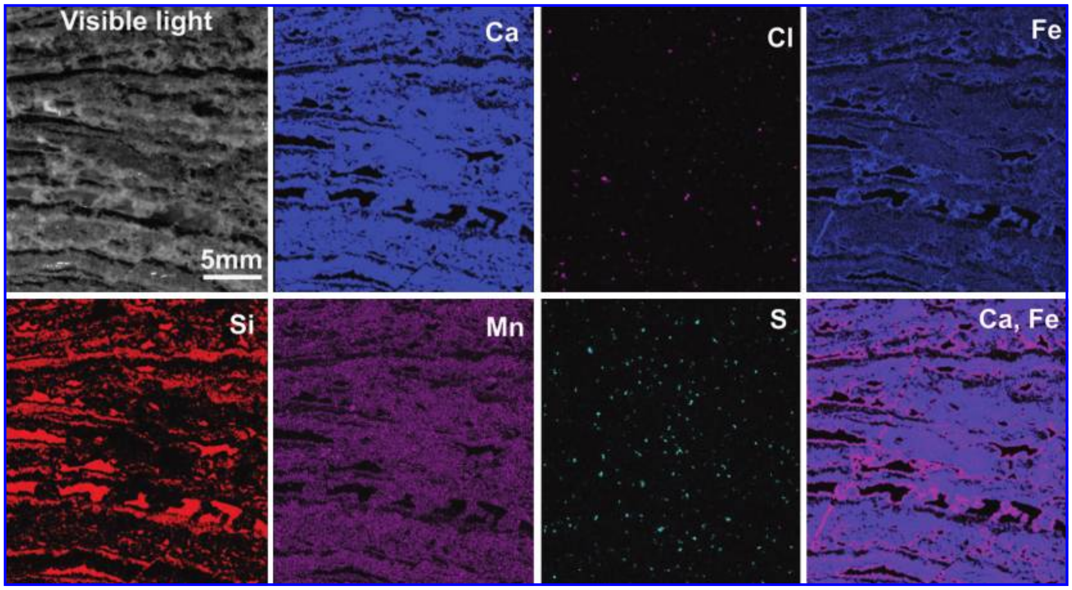

FIG. 6.3. Stromatolite from the Archean Strelley Pool Formation (Pilbara, Australia). Top left image is a polished slab, showing irregularly laminated dolomite and chert. Remaining images are element maps produced by XRF mapping over the same area. The lower right image consists of overlaid iron (red) and calcium (blue) maps, showing dolomite laminae and iron-rich dolomite cavity-lining cements that confirmed the presence of fenestrae—a key microbial fabric component. An APXS measurement would chemically homogenize the detailed variations existing at this scale.

of $-5°C$. Measurements can be taken by deploying the rover's robotic arm to place the instrument's sensor head in close contact with a sample. The sensor head containing radioactive ^{244}Cm sources bombards the sample with emitted alpha particles and X-rays. From the X-rays measured by the sensor head detector (equivalent to particle-induced X-ray emission and X-ray fluorescence techniques), the rough abundance of major elements can be obtained in 15 minutes, or a complete chemical analysis, including some trace elements, can be obtained in 2–3 hours, which requires a total of ~6 W with no cooler or ~10 W with the cooler (only required at the highest ambient temperatures) with an instrument mass of 1.7 kg. The 10 mm^2 silicon drift detector can achieve a full-width at half maximum at 5.9 keV of ~140 eV and covers the X-ray energy range from 700 eV to 25 keV with 1024 channels. In addition, backscatter peaks of primary X-ray radiation allow detection of bound water and carbonate at levels of around 5 wt % (Campbell *et al.*, 2008).

6.1.4. Green Raman imager (robotic arm–mounted). Raman spectroscopy is a point analysis method that uses energy loss from an excitation laser source due to lattice or molecular vibrations to discern the identity of the targeted material. Raman imaging is a new technique that rasters the point excitation source across an area to produce images instead of point measurements, and results in far more information. For example, a point Raman instrument on Mars could discover jarosite, but this reveals little more than is already known, namely, that jarosite exists in martian mineralogy. A Raman image containing jarosite (Fig. 6.4) would enable us to determine whether the jarosite exists as wind-blown fines, a weathering rind component, in a cement, in a breccia, as an alteration vein, as a constituent in a layered deposit, or as a deposit that fills vesicles, and so on (Vicenzi *et al.*, 2007; McCubbin *et al.*, 2009). Each of these settings can be used to describe the origin and alteration history of the target material. While commercial Raman imaging instruments are common and have achieved considerable maturity, no Raman imaging instrument, to date, has been developed for space flight. The Mars Microbeam Raman Spectrometer is the closest to this achievement (Wang *et al.*, 2003), as it can make linear scans and was proposed as part of the Athena rover payload. It was also considered for, but not flown on, the MERs. Commercial instruments can image areas 100 μm^2 up to multi-cm^2, with pixel sizes from ~1 μm^2 down to 360 nm^2. The primary limitation arises from native sample fluorescence, but there are technical means to minimize that effect. Mineral sensitivity is extraordinary and ranges from clay minerals to opaque minerals, to the full range of carbonaceous species (Schopf *et al.*, 2002; Steele *et al.*, 2007; Fries *et al.*, 2009; Papineau *et al.*, 2009) from diamond to organic compounds, and to every known silicate mineral. No sample preparation is necessary, but some surface grinding may be preferable. The flight instrument mass is estimated to be <6 kg and the power required <30 W, including electronics with a field of view of 1 cm^2 and a resolution of 4 μm.

6.1.5. Deep ultraviolet Raman/fluorescence mapper (robotic arm–mounted). Deep ultraviolet (DUV) Raman spectroscopy is well suited to *in situ* analysis of many carbonaceous compounds (Asher and Johnson, 1984; Storrie-Lombardi *et al.*, 2001; Hug *et al.*, 2006; Frosch *et al.*, 2007; Bhartia *et al.*, 2008). Rayleigh enhancement with deep UV excitation generates ~20 times greater signal strength than the same measurement made with a green excitation laser and greater than 100× over a red (785 nm) excitation laser. Resonance Raman effects in carbonaceous compounds under UV excitation produce additional signal improvement that

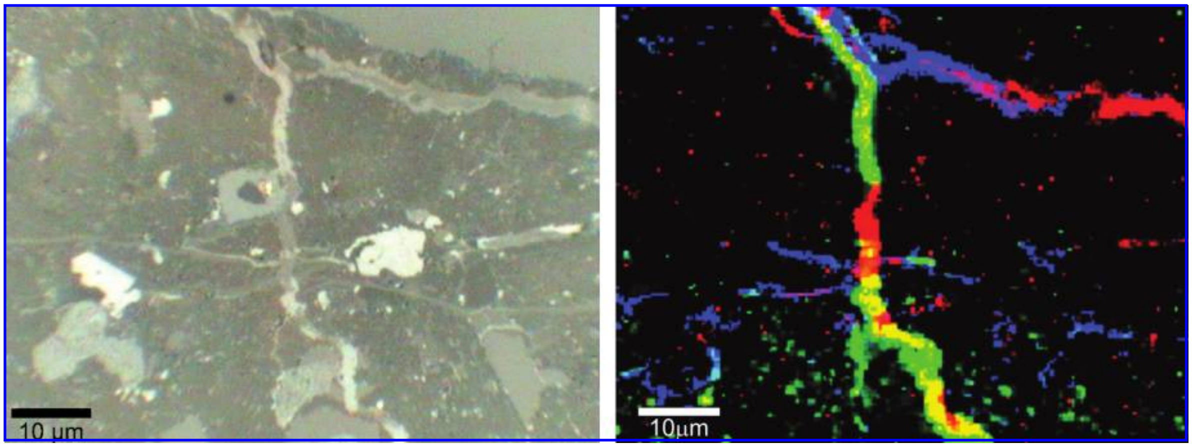

FIG. 6.4. (Left) 20× reflected light image of martian meteorite MIL 03446. (Right) Raman image from image at left. Red: jarosite. Green: goethite. Blue: clay minerals. This alteration vein is martian in origin as shown by D/H abundance ratio and the fact that the vein is truncated by the meteorite fusion crust (not shown). Data courtesy of M. Fries and A. Steele, Geophysical Laboratory, Carnegie Institution of Washington.

ranges up to 8 orders of magnitude (Asher and Johnson, 1984; Storrie-Lombardi *et al.*, 2001). Examples of resonantly enhanced bonds include, but are not limited to, water, C–H, CN, C = O, C = C, NH_x, NO_x, SO_x, PO_x, ClO_4, and OH with sensitivities in the sub–parts per million (Dudik *et al.*, 1985; Asher *et al.*, 1986; Burris *et al.*, 1992; Ianoul *et al.*, 2002). In addition to the resonance enhancements, with excitation below 260 nm, Raman and fluorescence regions do not overlap (Asher and Johnson, 1984; Frosch *et al.*, 2007). This enables simultaneous measurement of Raman spectra and fluorescence backgrounds (Bhartia *et al.*, 2008).

Coupling DUV Raman with DUV native fluorescence would enable characterization of biological materials as well as structure and arrangement of aromatic rings with sensitivities at the sub–part per billion (Bhartia *et al.*, 2008; Rohde *et al.*, 2008) (Fig. 6.5). These combined data sets make it possible to map the distribution of organic compounds and water (Fig. 6.6). This instrument can achieve a field of view of 1 cm^2, with spatial resolution of 10 μm, as a rover arm–mounted instrument mapping at a standoff distance of 2.5 cm. The mass and power consumption for this instrument is estimated to be $\sim$5 kg and <20 W, including electronics.

6.1.6. Imaging spectrometer (mast-mounted). The Mast-Mounted Imaging Spectrometer is a passive instrument that operates in the visible and short-wave infrared portion of the spectrum to provide detailed mineral maps of the surrounding terrain and the mineral composition of specific rocks and outcrops. Spatial resolution varies with distance from the target, reaching down to a few mm at distances below 10 m (example shown in Fig. 6.7). The instrument is capable of generating 360° panoramic image mosaics and providing compositional information for each pixel in the images. Its spectral range and spectral resolution are similar to those of the orbiting CRISM and OMEGA instruments, which allows for extension of the orbital measurements to higher spatial resolution in addition to providing "ground truth" data. Short-wave infrared spectroscopy has proven to be highly effective in mapping aqueous alteration deposits on Mars from orbit (Noe Dobrea *et al.*, 2009) and has been used to identify minerals such as hydrous sulfates and phyllosilicates on the martian surface (*e.g.*, Bibring *et al.*, 2005; Gendrin *et al.*, 2005; Langevin *et al.*, 2005), carbonates (Ehlmann *et al.*, 2008), opaline silica (Milliken *et al.*, 2008), and mineralogically complex regions with multiple types of

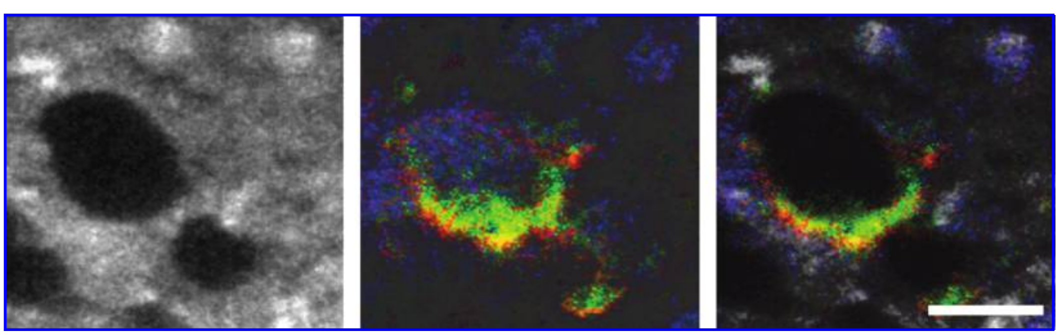

FIG. 6.5. DUV (<250 nm) excitation of native fluorescence from a basalt vesicle (dark area) from Svalbard, Norway. Left is a visible reflectance image. Center is a native fluorescence image. Fluorescence analysis (Bhartia *et al.*, 2008) indicates the presence of 2-ring aromatics (yellow regions) as possible mantle-derived organic compounds. Right is a visible and fluorescence overlay. White scale bar: 2 mm. Sample courtesy of A. Steele, Geophysical Laboratory, Carnegie Institute of Washington. For further information on the geology and geochemistry of a basalt from this locality, see Steele *et al.* (2007).

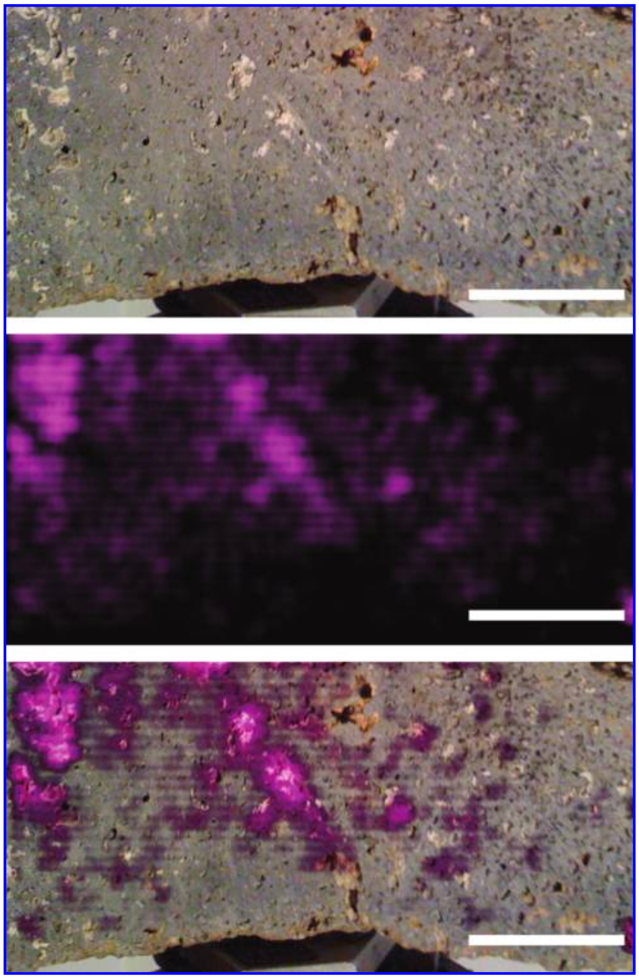

FIG. 6.6. DUV excited H_2O Raman map of an altered basalt from the Mojave Desert, acquired from a 2 m standoff (image = 20.3×7.6 cm). (Top) Visible reflectance image, white regions are composed of carbonates. (Center) False-color map of the OH-stretch Raman band showing the distribution of hydrated minerals (magenta color) indicating extent of fluidic alteration. (Bottom) Overlay of the reflectance and Raman map indicates carbonate deposited by aqueous transport and mixed with hydrous mineral phases. White scale bar: 5 cm.

clay minerals including iron- and aluminum-rich varieties (*e.g.*, Bishop *et al.*, 2008).

This medium- to low-risk instrument is expected to have a 3 kg mass and power requirements of 6 W, including electronics, optics, and thermal control. The instrument has no mechanisms other than the scanning in x and y provided by the mast. A single data set will typically comprise an area of 344×344 spatial pixels (1 $mrad^2$) with a single-line field of view of 1 mrad×20 degrees. Each pixel is simultaneously imaged in ~420 spectral bands over a range of 400–2500 nm where the spectral resolution is 5 nm.

6.2. Instrument development

Preliminary scheduling for a mission project of this kind indicates that the instrument competition might take place in late 2012, with instrument selection about 6 months after that. Candidate instruments need to be at about TRL-5 or greater to be credibly proposed. This means that during the next 2 years significant instrument funding through NASA's Mars Instrument Development Program (MIDP), Planetary Instrument Definition and Development Program (PIDDP), and similar programs would need to be made available to the community. Instrument competitions should include specific needs related to the proposed MAX-C mission. As discussed above, because many of the instruments of high relevance to the MAX-C mission concept are at a readiness state less than TRL-5, the definition of a straw-man payload suite, which must be done immediately for engineering trade studies, will necessarily be immature. To the extent possible, the results of early engineering trade studies should be fed back into instrument development constraints and priorities.

MAJOR FINDING: For these instruments to be mature enough to be selectable for flight (*i.e.*, TRL-6), a commitment must be made now and sustained for the next several years to improve the maturity of the most promising candidate instruments.

7. Relationship to a Potential Sample Return Campaign

To analyze the relationship of the proposed MAX-C mission to the possible future return of samples from Mars, it is

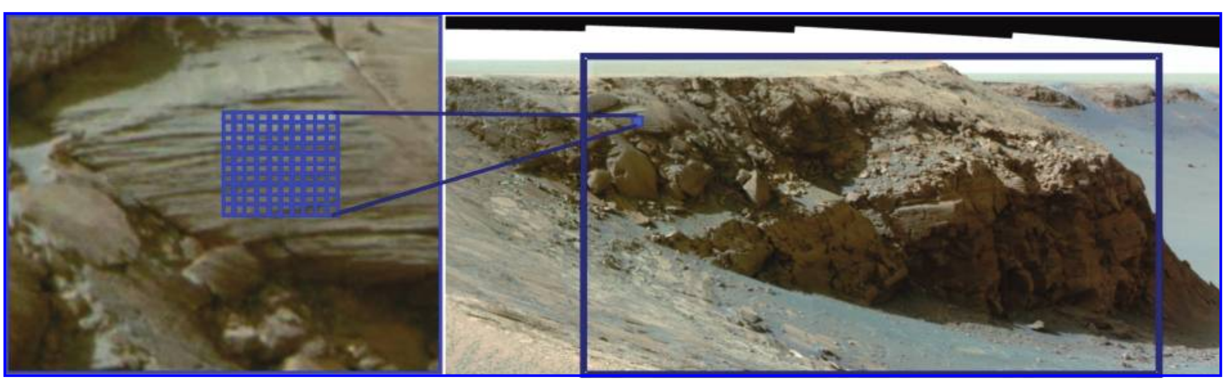

FIG. 6.7. (Right) Example color image mosaic of Cape St. Mary, a promontory on the rim of the Victoria Crater, Mars, acquired by Pancam on Opportunity rover. The observation spans 36°×20° (620×344 pixels). (Left) A 10×10 square pixel area is expanded, showing the ability to resolve differences within layers. Pancam image credit: NASA/JPL-Caltech/Cornell University. The Mast-Mounted Imaging Spectrometer would provide visible through shortwave infrared spectra for each pixel.

necessary first to consider some of the aspects of sample return. The potential sample return objectives, sample acquisition and preservation requirements and strategies, and sample context requirements are relevant planning considerations. In Section 7.2, we discuss how the proposed MAX-C mission would fit into a larger possible mission architecture configuration. The expectation is that the potential MAX-C sample cache would be a returnable and scientifically enticing cache that the science community would be eager to see returned to Earth (Section 7.3).

7.1. Proposed Mars sample return scientific objectives and required measurements

7.1.1. Potential sample return scientific objectives. A potential sample return campaign would carry an unprecedented combination of cost and risk, and because of this must return unprecedented scientific value. The value of a potential Mars sample return has been discussed in the literature for at least 30 years (see, for example, NRC, 1978, 1990a, 1990b, 1994, 1996, 2003, 2006, 2007), and the scientific rationale for returning samples has evolved over time. Early studies (*e.g.,* NRC, 1978) emphasized the need for samples to better understand the evolution of the planet. Emphasis in the last two decades, on the other hand, has been on the search for past and present life (*e.g.,* NASA, 1995; NRC 2007). Answering the life question ("Are we alone?") is now one of the most important strategic drivers for NASA (NASA Strategic Plan), and the Mars Exploration Program has therefore long carried the objective "determine whether life ever arose on Mars" as one of its top priorities. Returning samples from Mars is considered essential for meeting that objective.

In accordance with these considerations, the MEPAG ND-SAG (2008) reached the following conclusions after carrying out a detailed analysis of the scientific trade space associated with the objectives and implementation options of a potential sample return campaign:

- Many scientific objectives could be achievable with a sample return campaign (11 objectives listed in MEPAG ND-SAG, 2008), depending on where it would be sent, what kinds of samples it could acquire, and in what condition they would be returned. Unfortunately, some objectives require relatively specific samples, and there is probably no single place on Mars where a suite of samples could be collected that would achieve all these objectives. Thus, planning for a potential sample return must involve careful consideration of the priority of its scientific objectives, the influence this prioritization has on choice of landing site, and criteria for selection of samples at that site.
- The most important scientific objectives of a potential sample return mission should relate to "the life question" (see also NRC, 2007; iMARS Working Group, 2008; MEPAG, 2009).

Because of the significance of the life question to Mars exploration, we conclude that returned samples from Mars must make a substantial contribution in that area. *For many reasons,* however, a significant contribution must also be made toward at least one of the other high-priority objectives that have been defined by the Mars scientific community.

FINDING: For a potential Mars sample return mission to deliver value commensurate with the cost and risk, it must address a major life-related objective *as well as* one or more of the major geological objectives defined by the MEPAG ND-SAG (2008).

7.1.2. The kinds of samples needed to achieve these objectives: diverse, intelligently collected samples. The NRC (1978) first concluded that a potential Mars sample return mission must return "an intelligently selected suite of martian samples," and this recommendation has been reinforced by subsequent panels ever since. A primary theme of the ND-SAG report was to emphasize the need for careful selection to ensure geological diversity (MEPAG ND-SAG, 2008). This is especially true for addressing the life question, because detecting and interpreting potential evidence of microbial life requires assessment of the paleoenvironment, its habitability and biosignature preservation potential, and the relationships of potential biosignatures within the paleoenvironmental context. Moreover, the sampling should take strategic advantage of the contextual framework to allow robust testing of different hypotheses that arise. Evidence of life is not likely to be something that resides in a single sample: rather, evidence of life emerges from an assemblage of observations, strategically analyzed and integrated across all scales of observation. This is unequivocally illustrated by the challenges and spirited debate surrounding the search for Earth's earliest biosignatures (*e.g.,* Walsh, 1972; Lowe, 1980, 1983, 1992, 1994; Walter *et al.*, 1980; Buick *et al.*, 1981; Awramik *et al.*, 1983; Walter, 1983; Walsh and Lowe, 1985; Byerly *et al.*, 1986; Schopf and Packer, 1987; Schopf, 1993, 2006; Grotzinger and Knoll, 1999; Hofmann *et al.*, 1999; Hofmann, 2000; Ueno *et al.*, 2001; Westall *et al.*, 2001, 2006; Brasier *et al.*, 2002, 2006; Van Kranendonk *et al.*, 2003; Lindsay *et al.*, 2003a, 2003b, 2005; Tice and Lowe, 2004; Moorbath, 2005; Allwood *et al.*, 2006, 2009; McCollom and Seewald, 2006; Westall and Southam, 2006; Westall, 2007).

FINDING: Particularly in the case of a "signs of life" objective, a potential sample return mission should be designed to return a set of intelligently collected, diverse samples.

One advantage of returning samples is that the investigations could generate results much more definitive than those achievable by *in situ* techniques alone. This lesson has been learned over and over again by geologists working in the field on Earth. However, an extension of this lesson is that the scientific productivity of the samples would be strongly dependent on their character. For example, as pointed out by the ND-SAG (2008), returning 24 identical rocks would have no more scientific value than returning one. For this reason, we introduce the concept of "outstanding samples," or perhaps more properly, "outstanding sample suite." On the one hand, we agree with the position (most recently summarized by NRC, 2007) that there is no such thing as "the ideal sample" and that delaying a potential sample return campaign until it is discovered is illogical. On the other hand, even though any sample returned from Mars would be useful for some aspect of scientific inquiry, it is also true that not all samples would be equally useful for the kinds of scientific questions we are trying to answer. Moreover, the concept of a suite of samples is rooted in the premise that the differences between samples is as important, or even more so, than the absolute properties of any of them. Thus, a well-collected suite of samples would be one that represents the range of natural variability of a key martian geological process. A couple of examples to illustrate the point are shown in Fig. 7.1.

In both of the examples in Fig. 7.1, there is more than one way to assemble an effective suite of samples, and equally effective suites could be collected at other nearby localities. The common point, however, is the identification of samples that span the range of natural local diversity is required in order to make effective sample selection decisions. Such samples would be more than "ordinary" and less than the "right" sample—for this we use the term "outstanding" samples. Clearly, the acquisition of a set of outstanding samples would take planning and effort.

FINDING: To meet the high expectations, a potential sample return mission should return "outstanding samples" that have the potential to generate results more definitive than those achievable *in situ* and could make a significant contribution to addressing MEPAG's life-related scientific objectives.

Seeking signs of life demands a host of scientific investigations that would yield important *in situ* results in their own right. Furthermore, such results would also provide essential information for addressing other high-priority scientific objectives. Thus, very little scientific trade-off is required between simultaneously optimizing feed-forward to a "signs of life" potential sample return campaign and conducting significant *in situ* science in multiple high-priority research areas.

7.1.3. Measurements needed to make sample selection decisions and to document sample context. As noted by the MEPAG ND-SAG (2008), to interpret analytical results obtained from potential returned samples, the geological context of the landing site should be fully documented. Such documentation should include mapping bedrock and other surficial rocks, mineralogy, geochemistry, and petrology. Thus, any potential sample suite must be characterized *in situ* and be designed to leverage the geological context to aid in the interpretation of eventual Earth-based laboratory analyses. Achieving these requirements would substantially influence landing site selection and rover operation protocols. The importance of access to outcrops would necessitate either significant traverse capability or hazard avoidance during descent (see Section 10.2).

The MEPAG ND-SAG (2008) proposed two instrument suites for a potential sample return mission: one designed for a mission sent to a previously visited site and the other for a mission going to a new site (Table 7.1). The MRR-SAG agrees that, at the bare minimum, the potential sample acquisition rover must make the ND-SAG's minimum observations for a new site:

(1) Color stereo imaging,
(2) Microscopic imaging,
(3) Elemental and mineralogical determinations,

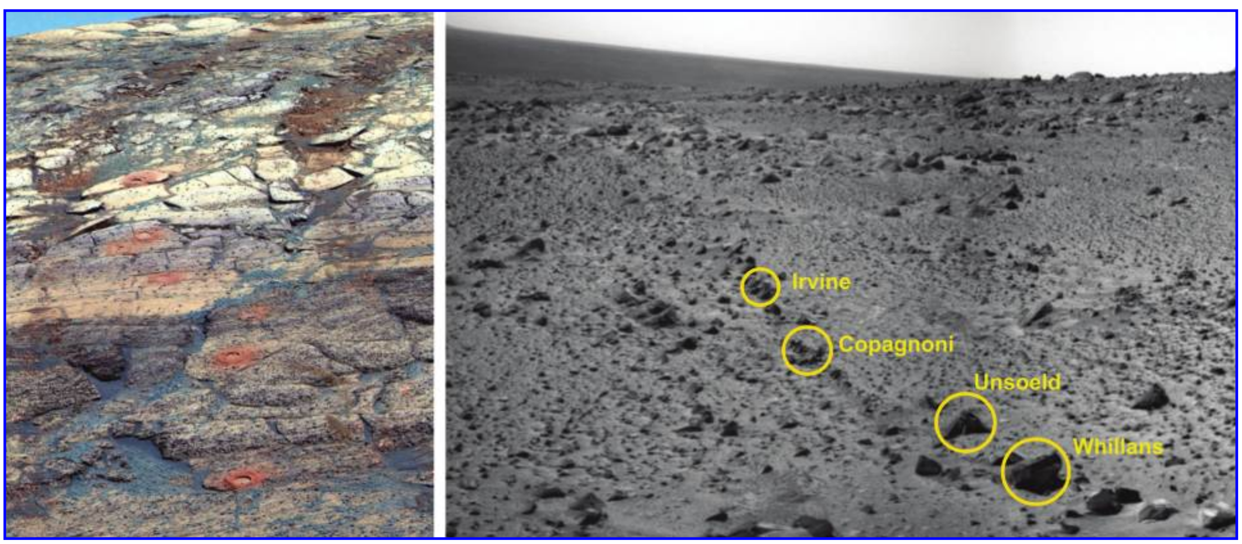

FIG. 7.1. Two examples (S.W. Squyres, written communication, 2008) highlighting the importance of sample selection tools in understanding the range of natural variation, which is crucial in assembling a suite of outstanding samples. (Left) False-color rendering of a Pancam image mosaic from Opportunity rover on Sol 173 (July 19, 2004). The view, looking back up toward the rim of Endurance Crater, shows the rover's tracks and the first seven holes made by the RAT as the rover moved down layers of exposed rock. Image credit: NASA/JPL-Caltech/Cornell. (Right) A new type of basalt was detected with Spirit rover's Mini-TES at the summit of Husband Hill (McSween *et al.*, 2006), at this location shown in a Navcam mosaic from Sol 598. The rock named Irvine, which was part of an aligned set of similar rocks (some of which are circled in yellow), was more closely examined with instruments on the robotic arm. Characterization of the difference between the alkaline basalt Irvine and other more common subalkaline basalts allowed interpretation of the liquid line of descent—this would not have been possible if this type of sample had not been recognized. In addition to the need for macroscopic target selection, sample acquisition decision-making would also need to incorporate observations from finer scale, such as those in Fig. 6.1 and possibly also the other figures in Section 6. Image credit: NASA/JPL-Caltech.

Table 7.1. Recommended Required Instrumentation for a Potential Caching Rover that is Directed to a New Landing Site or to a Previously Visited Site

		ND-SAG		MRR-SAG	
What would be needed	*Measurement*	*New site*	*Previous site*	*New site*	*Previous site*
Ability to locate samples	Color stereo imagery	YES	YES	YES	YES
	Remote mineralogy			YES	YES
Ability to determine fine rock textures (grain size, crystal morphology), detailed context	Microscopic imagery	YES	YES	YES	YES
Ability to differentiate rock types, effects of different natural processes	Mineralogy	YES	NO	YES	YES
Ability to differentiate rock types, effects of different natural processes	Bulk elemental abundance	YES	NO	YES	YES
Ability to detect organic carbon	Organic carbon detection	YES	NO	YES	YES
Ability to remove weathered or dust-coated surface and see unweathered rock	Abrasion tool	YES	NO	YES	YES

The left-hand part of this table was developed by the ND-SAG (2008; Table 6). The MRR-SAG reached consensus on the right two columns, identifying the same payload that would be required for a new site as for a previously visited site.

(4) Detection of reduced carbon,
(5) Ability to remove weathered or dust-coated surfaces (*i.e.*, an abrasion tool).

The ND-SAG noted that it is theoretically possible for a potential sampling rover that revisits a previously explored route at a well-characterized site to carry reduced instrumentation (indicated by the pink boxes in Table 7.1). However, this would mean that the potential rover might need to revisit exact positions, and possibly the same RAT holes, if the compelling rock features are difficult to find and document with just cameras (as the ND-SAG recommended). Since such a mission would have to rely on cameras for all of its selection and documentation of samples, the risk of not being able to reoccupy exact locations that were characterized by the previous (MER or MSL) mission is a potentially crucial vulnerability with extremely negative consequences to the scientific return. The MRR-SAG concluded that the same payload would be required, whether the potential sample acquisition rover is sent to a new or a previously visited site (Table 7.1, right two columns). In addition, the MRR-SAG updated Table 7.1 to indicate that the mineralogy information should assist with both the location of samples from a distance (purple boxes in Table 7.1) and the characterization of samples at higher spatial resolution. The ND-SAG did not specify the exact nature of the recommended required mineralogy measurements, other than the need to differentiate rock types and effects of natural processes.

FINDING: The potential rover needed to do scientific sample selection, acquisition, and documentation for potential return to Earth should have similar measurement capabilities, whether it is sent to an area that has been previously visited or to a new unexplored site.

The MRR-SAG notes that this recommended minimum required set of observations would be greatly improved with various "upgrades," if they could be accommodated. Such upgrades would include the capability to evaluate chemistry and mineralogy of small-scale features and capability of evaluating constituents of interest to astrobiology in addition to reduced carbon (such as N, S, and biosignatures). Based on experience from MER, where the science team had difficulties inferring orientation of underground bedding, the inclusion of a subsurface sounding instrument such as ground-penetrating radar would also add valuable context.

The potential sample acquisition rover should carefully document the context of its collected samples and should be robust against any challenges impinging on the proposed scientific objectives. For example, several likely scenarios exist where the potential sample acquisition rover might be unable to access and sample the exact spot(s) where MSL might make compelling discoveries. Indeed, a well-equipped potential sample acquisition rover could make its own novel discoveries at a MER or MSL site. The ability of a potential sample acquisition rover to stand alone in its ability to execute a scientifically valuable mission would also add considerable robustness to a potential sample return campaign. Of course, future MER or MSL discoveries could help to optimize the measurement capabilities of a sample acquisition rover and thereby enhance even further the scientific return of the overall potential sample return campaign.

FINDING: (1) The potential sample acquisition rover must provide the data needed to find and select samples and to establish their context over a wide range of scales. (2) The baseline instrument package might need to be modified, depending on the specifics of what the MERs or MSL find, if the potential sample acquisition rover returns to one of those previously visited sites.

7.2. How the proposed MAX-C mission fits in a potential 3-element sample return campaign

Given current understanding of celestial dynamics and engineering approaches to optimize spacecraft design, it is

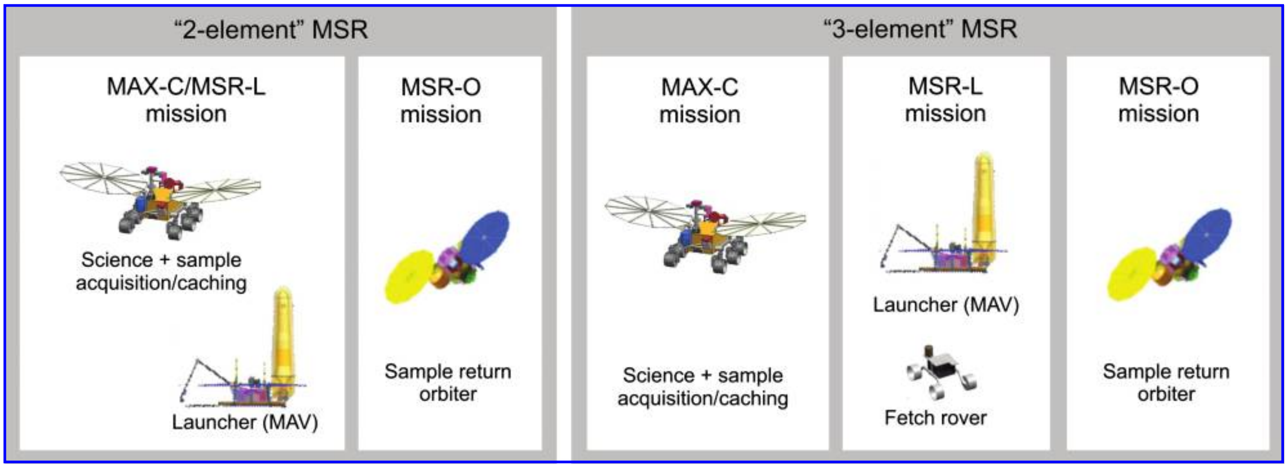

FIG. 7.2. Schematic diagram depicting the 3-element mission campaign concept to accomplish a potential return of samples.

widely accepted that the return of samples from Mars would involve a potential campaign of multiple missions (see *e.g.,* iMARS Working Group, 2008; Borg *et al.,* 2009). The proposed MAX-C mission would be intended to be the first step of a potential 3-element campaign (Fig. 7.2), followed by another potential mission (MSR-Lander) carrying a small rover that would fetch the proposed MAX-C cache (*i.e.,* surface rendezvous) and also carrying a MAV capable of launching a container holding the proposed cache into orbit for rendezvous with an orbiter mission. A 3-element architecture would offer some major financial advantages in the form of smoothing future budget peaks for the Mars flight program (*e.g.,* Li, 2009).

7.2.1. Considerations related to a potential 3-element campaign. Exploring a site prior to sending the potential sample return system (*i.e.,* lander and MAV) would reduce both engineering and scientific risk for the overall potential sample return campaign. Many scientists and engineers have previously concluded that it would be too risky to send the mission that would land the MAV to a site other than one that has been previously visited (MacPherson *et al.,* 2005; discussions at the MSR workshop in Albuquerque, May 2008); and, after extensive debate within the team, the MRR-SAG strongly endorses that conclusion.

FINDING: In order for a potential sample return campaign to be of acceptable risk (both science and engineering), the potential MSR-Lander mission should be sent to a site previously explored by a rover or lander.

We would know that the samples exist, are retrievable, and are of sufficient scientific interest before committing to sending the potential lander mission with the MAV. Moreover, we would have completed exploration and documentation of the geological context with a payload optimized for science. Sending the MAV in a launch opportunity after the proposed MAX-C rover would allow it to be launched with a more modest fetch rover (requiring a minimal payload and briefer surface operations time).

For the potential 3-element approach, the MAV would not be put "at risk" until after the cache has been prepared, thus making it more likely that the proposed MAX-C rover would be allowed to visit a site that has not been previously ground-truthed. Allowing a broader range of landing sites to be considered is a significant scientific benefit of a potential 3-element campaign (as discussed in Section 9.2). The intention would be to fly the MAV in a follow-on launch opportunity, but the go/no-go decision could be made after the proposed MAX-C mission. In a 3-element campaign, after arrival on Mars, the proposed MAX-C rover would likely have plenty of operations time (depending on rover lifetime and which launch opportunity would be used for the mission carrying the MAV) to collect a thoughtfully selected, thoroughly documented, diverse set of samples from a well-characterized geological setting.

FINDING: A potential 3-element MSR campaign would result in great simplification of the MSR-Lander mission. By reducing the number of miracles that mission would require, the overall campaign would be more technically feasible.

In a 3-element campaign, the proposed MAX-C rover mission would be required to make quality sample selection decisions, document the context of the samples chosen, and acquire and cache the samples chosen. The instruments necessary to provide the informational basis for these decisions would also need to be present to achieve the *in situ* objectives.

In summary, the proposed MAX-C rover could benefit the potential sample return campaign in the following ways:

(1) Developing and accomplishing rock coring and encapsulation.
(2) Assembling a cache containing sample suites acquired from a diverse set of sampling locations.
(3) Accomplishing #1 and #2 above, consistent with sample return planetary protection and contamination control requirements (MEPAG MRR-SAG, 2009).
(4) Preparing and operating a new generation of instruments optimized for sample selection and site characterization.
(5) Further verifying the performance of the MSL EDL system and improving targeting accuracy. This would also benefit the later potential mission carrying the MAV and fetch rover.

FINDING: The proposed MAX-C mission would help prepare for a potential sample return in at least five critical areas—thereby significantly reducing the "number of miracles" needed for an overall sample return campaign.

On the other hand, sample caching would consume critical mission resources (*e.g.,* money, mass, and surface operation time) that could have been used for *in situ* scientific operations. For example, a drill on an instrument arm would increase the vibration isolation design requirements for the scientific instruments on the arm.

FINDING: Caching samples on the proposed MAX-C mission would be of major engineering benefit to potential sample return, but this would come at a cost to *in situ* science of the proposed MAX-C mission. The importance of a sample return makes this trade worthwhile.

7.2.2. Possible risk reduction engineering measurements in a potential 3-element campaign. By virtue of the potential 3-element campaign, the proposed MAX-C rover might be able to carry out certain specific tests that would buy down engineering risks for the follow-on parts of the campaign. We present one example related to electrical fields but encourage further discussion by future planning teams. Theoretical predictions and laboratory simulations suggest that electrostatic charging could be a serious risk to the launch of a MAV from the martian surface, but scientists do not have sufficient information to confirm the magnitude of the risk (Melnik and Parrot, 1998; Farrell *et al.,* 1999; Farrell and Desch, 2001; Michael *et al.,* 2008). Electrical discharge in dust storms (Farrell *et al.,* 1999) and rocket-triggered lightning along the exhaust trail of a MAV during ascent from Mars (MEPAG HEM-SAG, 2008) are a possible concern. The potential MAX-C rover could include a device that monitors electric fields (*e.g.,* Farrell *et al.,* 1999; Berthelier *et al.,* 2000) to determine the magnitude of the risk and affect the design of the MAV so that it would be robust in the local martian conditions. An electric field probe with a mass of ~ 0.5 kg requiring ~ 1 W has some MIDP heritage (MEPAG HEM-SAG, 2008). Future design teams should determine the specific nature of the electric field information needed to significantly reduce risk of the MAV launch, and assess the feasibility of achieving and accommodating those measurements with an *in situ* instrument.

There could be other measurements like this, or engineering design implementations of the proposed MAX-C mission that should be considered, that would reduce the cost and risk of the other missions that are part of the overall potential sample return campaign. This is left to future study groups and engineering teams to determine.

7.3. The proposed MAX-C sample cache—intent to return

It is not possible to know in advance what would be discovered at any individual landing site on Mars. Our orbital data sets are of very high quality, but we know from the experience at both MER sites that orbital data can give incomplete representations of the surface geology. For example, at the Opportunity site, the orbital data show the presence of hematite but not sulfate; and, in actual fact, both can be detected from the ground. However, a crucial point is that this committee has concluded that, to within reasonable levels of confidence, a high-quality landing site for the assembly of a sample cache can be selected from orbital data, and the intent is that the samples selected at that site would actually be returned if the follow-up MSR mission were approved. It would be unwise to make this decision formally before the potential sample collection and caching missions take place, and it is possible to envision scenarios in which the proposed MAX-C cache would end up with lower-than-expected scientific priority (for example, if the rover fails to access certain high-priority sampling targets). However, the baseline intention is that the proposed MAX-C cache would be returned, and mission planning should be carried out on this basis.

8. Consensus Mission Vision

As discussed at the recent (July 29–30, 2009) MEPAG meeting at Brown University (http://mepag.jpl.nasa.gov/meeting/jul-09/), the Mars Exploration Program appears to be moving forward from a strategy of "follow the water" and examining habitable environments toward one of "seek signs of life." Also included in the strategy is preparation for a potential Mars sample return. To further focus the proposed MAX-C mission toward a single concept, the MRR-SAG considered how the investigations and measurements proposed for the top three concept missions meet the overall vision of a mission to the martian surface that would (1) have the *in situ* scientific exploration capability to respond to discoveries by prior landers or orbital mapping missions, (2) be able to collect, document, and cache samples for potential return to Earth by a potential future mission, (3) be a key stepping stone to seeking signs of life on Mars, and (4) do all this within the constraints of a rover intermediate in size to MER and MSL. Additionally, the MAX-C mission concept must take into account areas in which it would complement, and be complemented by, ESA's ExoMars mission.

8.1. Consensus mission concept

As described in Sections 6 and 7.1, the measurements needed to achieve the proposed *in situ* objectives are the same measurements needed to select samples for potential return to Earth and document their context.

***MAJOR* FINDING: The instruments needed to achieve the proposed *in situ* objectives are the same instruments needed to select samples for potential return to Earth and document their context. Because of the compelling commonalities, it makes sense to merge these two purposes into one mission.**

This consensus mission concept has recommended objectives consisting of three components:

(1) A set of primary objectives related to the exploration of a site on Mars. Given current scientific priorities, the proposed rover would need to visit a site with high preservation potential for physical and chemical biosignatures and, at that site, achieve the following primary objectives: (a) evaluate paleoenvironmental conditions, (b) characterize, *in situ,* the potential for the preservation of biotic or prebiotic signatures, and

(c) access a sequence of geological units in a search for evidence of past life or prebiotic chemistry. Note that steps (a) and (b) above cannot be done once for the planet, such that the investigation would be considered complete—these activities would need to be done at every site where the potential signs of life are being investigated.

(2) A primary objective to collect, document, and package in a manner suitable for return to Earth by a potential future mission at least some of the samples needed to achieve the scientific objectives of a sample return mission. These samples should include some of the rocks that contain the essential evidence for the interpretations reached as part of Objective #1 above but would also certainly include additional types of samples. As documented by the ND-SAG (2008), a potential sample return would have important objectives beyond those related to the life goals, and multiple sample types would be implied, including samples of rock, soil, and atmosphere. It is yet to be determined whether the proposed MAX-C mission should be designed to collect rock samples only or collect soil samples as well (it might be possible to collect soil samples via the proposed mission that would carry the MAV).

(3) At least one secondary scientific objective, the highest priority of which is related to measuring the surface atmospheric pressure as a function of time.

SUMMARY OF SCIENTIFIC OBJECTIVES PROPOSED FOR THE MAX-C MISSION CONCEPT:

(1) ***Primary Scientific Objectives:*** **At a site interpreted to represent high habitability potential, and with high preservation potential for physical and chemical biosignatures:**
- **evaluate paleoenvironmental conditions**
- **characterize the potential for the preservation of biotic or prebiotic signatures**
- **access multiple sequences of geological units in a search for possible evidence of ancient life or prebiotic chemistry**

(2) Samples necessary to achieve the proposed scientific objectives of the potential future sample return mission would be collected, documented, and packaged in a manner suitable for potential return to Earth.

(3) ***Secondary Scientific Objective:*** **Address the need for long-term atmospheric pressure data from the martian surface.**

In summary, the proposed MAX-C mission should provide insight into the paleoenvironment of the landing site to help constrain the conditions in which life might have evolved on Mars. Visiting terrains that represent key periods in martian history (*e.g.,* the early Noachian, or the Noachian-Hesperian boundary) could enable investigation of a prebiotic environment or an environment that represents a period when Mars' climate and geology might have been in transition and affected the development of primitive cellular life. Investigation of an astrobiologically relevant environment represented by a novel terrain not previously explored could permit tests of hypotheses that relate to life in certain types of compositional or geomorphological environments. Detailed characterization of the geology of the landing site is critical to our understanding of conditions that may have enabled or challenged the development of life or that might have context that would guide the search for evidence of ancient life or prebiotic chemistry within the landing site region and more broadly across Mars. The concept of the payload needed to achieve all the objectives, including caching samples, is summarized in Fig. 8.1.

With respect to potential sample return, the proposed MAX-C mission could contribute greatly to our preparedness by caching samples, conducting site characterization (accomplished in large part via the primary *in situ* scientific objectives), and demonstrating key capabilities such as sample acquisition and manipulation, sample encapsulation and canister loading, and planetary protection and contamination control. Inclusion of these scientific approaches and technological components on the proposed MAX-C mission could, via early demonstration of sample acquisition and storage capabilities, substantially reduce the risks associated with sample return and enhance the quality and value of the science and technology required for a follow-on potential sample return mission.

9. Considerations Related to Landing Site Selection

In this section, the possible implications of novel discoveries by preceding missions on the design and implementation of the proposed MAX-C mission are considered, and a strategy is revealed for selecting a site that could bolster the scientific return of a potential sample return mission.

Discoveries by preceding orbiters and landers could impact the execution of the proposed MAX-C mission in several important ways. For instance, a compelling discovery at a particular locality would clearly impact the proposed MAX-C site selection process. Furthermore, the particular features identified at such a site might influence the selection of scientific instruments that would be required to perform the key types of measurements at the site. Geographical and other attributes of a landing site could influence the engineering design of the spacecraft. Possibilities such as these require consideration for how a future mission might adapt to such discoveries. Another consideration should be that, if the proposed MAX-C mission is sent to a previously visited site, then Mars exploration resources would become heavily concentrated at that single site, which would thereby potentially reduce (or slow) our efforts to better understand global martian geological diversity and character of diverse habitable environments.

FINDING: The best way to evaluate the multiple candidate sites from which to consider returning samples is via an open landing site selection competition with sample return selection criteria. A mission such as the proposed MAX-C presents the first opportunity to evaluate new high-potential sites via such a competition.

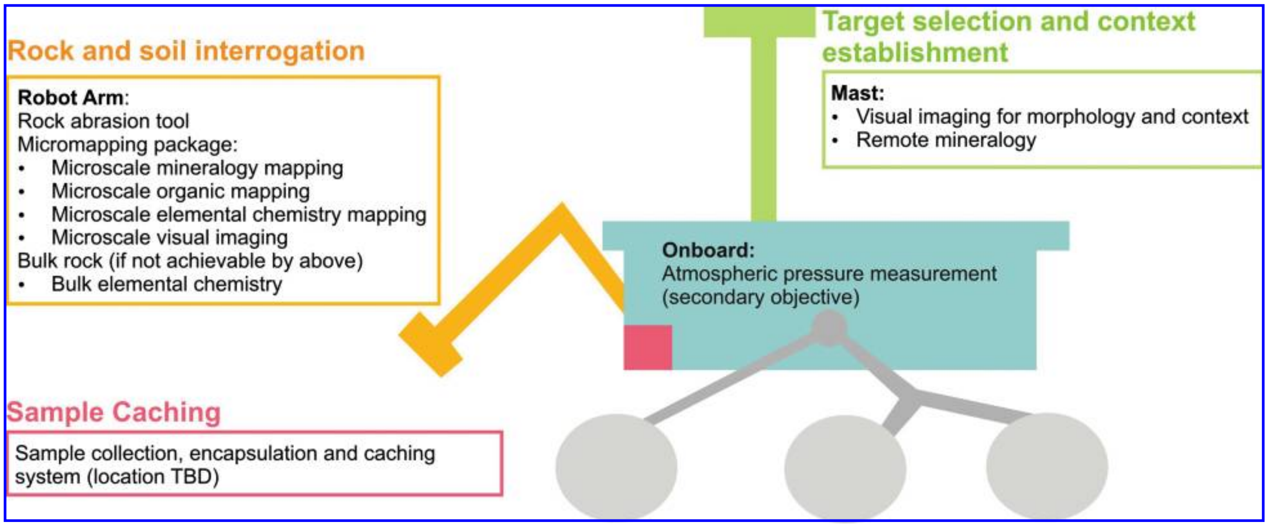

FIG. 8.1. MAX-C payload concept.

9.1. Discoveries potentially affecting landing site selection

Site selection is centrally important for pursuing key scientific objectives by reading a well-preserved geological record of ancient planetary processes and environments. Site selection is particularly critical for astrobiology, given the challenges associated with locating evidence of life on Mars, which might be akin to "finding needles [biosignatures] in a haystack [the vast martian surface]." Recent discoveries have revealed many different types of sites that were (or are) potentially habitable and might preserve evidence of life. Each of these types must be evaluated to determine its potential value as an exploration target. For example, in the search for evidence of past environments and life, each of the following key questions sets the stage for addressing the question that follows it: Was a particular local environment habitable at some time in the past? If so, did local conditions favor the preservation of evidence of environments and life? If so, are any organic compounds or other potential biosignatures present? If so, does the evidence indicate specifically that at least some chemical species, isotopic patterns, minerals, rock textures, or gaseous species probably originated from martian life and that an abiotic origin is unlikely? Findings by the Mars orbiters and landers that precede the proposed MAX-C mission would enhance the potential MAX-C site selection process (Fig. 9.1) and optimize the spacecraft design and scientific payload.

9.1.1. Orbiters. Recent remote sensing observations illustrate how an ongoing orbital campaign will help to evaluate candidate sites with regard to habitability and the potential preservation of a record of past environments and life. Minerals associated with aqueous processes occur in perhaps nine or more classes of deposits characterized by distinct mineral assemblages, morphologies, and geological settings (Murchie *et al.*, 2009). Phyllosilicates appear in numerous different settings, including the following: compositionally layered strata that are hundreds of meters thick and overlie eroded Noachian terrains, lower layers of depositional fans within craters, potential chloride-rich deposits on inter-crater plains, and deep bedrock exposures in thousands of craters (*e.g.*, Schwenzer *et al.*, 2009) and escarpments. Carbonates appear in thin unit(s) along the western margin of the Isidis Basin. Hydrated silica accompanies hydrated sulfates in thin layered deposits in Valles Marineris. Hydrated sulfates and crystalline ferric minerals co-occur in thick, layered deposits in Terra Meridiani and in Valles Marineris. Sulfates, ferric minerals, and kaolinite appear in deposits within some highland craters. While these discoveries exemplify successful outcomes of the Mars exploration theme "Follow the Water," additional orbital observations would be required to determine which of these numerous localities has the greatest probability of supporting life in the past and preserving an accessible biological record.

Assemblages of minerals formed in ancient environments frequently can indicate whether an environment provided

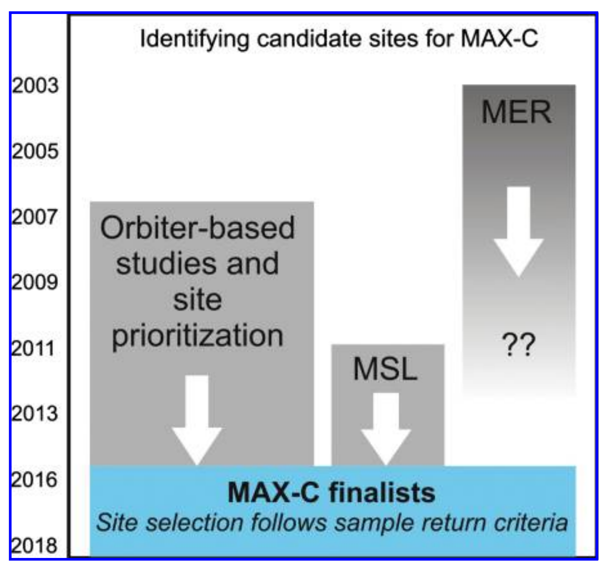

FIG. 9.1. Discoveries made by orbiters and landers during the next several years will influence substantially the selection of the proposed MAX-C candidate landing sites.

the requirements to sustain life, which would include essential nutrients, biochemically useful energy, and liquid water with a sufficiently high chemical activity to sustain life. The suites of minerals that have been detected to date indicate a range of soluble cations, pH, Eh, and water activities (Murchie *et al.,* 2009). When combined with chemical modeling, these observations provide a basis for constraining the pH and water activities of their environments of formation (Tosca *et al.,* 2008). For example, most smectite clays form in near-neutral waters, whereas kaolinite and hydrated silica can also form under weakly acidic conditions. Carbonates typically form in weakly alkaline environments and precipitate at water activity values that can sustain microbial life as we know it. Accordingly, deposits that are probably Noachian age and contain phyllosilicates and carbonates apparently formed in environments that had pH and water activity values consistent with habitable conditions (Murchie *et al.,* 2009). Phyllosilicates in ancient plains sediments appear to be dominantly detrital and also lack evidence for sulfates or carbonates, which is consistent with the possibility that the water activity might have been high. Phyllosilicates that lie deeper in the crust and have been exhumed locally probably formed in neutral to mildly acidic pH conditions. Orbiters have not yet detected mineralogical evidence indicating that these deposits formed in environments that had high salinities.

In contrast, late Noachian and younger evaporite deposits may have formed in water environments that were marginally habitable at best due to low water activity, at least at the time when their most soluble salt components were precipitated. The Meridiani layered deposits at the Opportunity landing site contain highly soluble magnesium sulfates and jarosite and thus apparently formed in waters that were both acidic and highly saline (Knoll *et al.,* 2005; Tosca *et al.,* 2008). The presence in some intra-crater phyllosilicate deposits of hydrated Fe and Mg sulfates and the acid sulfate alunite indicates extreme salinities and low pH. Monohydrated Fe and Mg sulfates in some Valles Marineris deposits precipitated from brines whose water activities were perhaps too low to sustain active metabolism. In contrast, gypsum ($CaSO_4 \cdot 2H_2O$) is estimated to have precipitated from martian brines whose water activities were higher (Tosca *et al.,* 2008) and, therefore, might have sustained biological activity. Occurrences of hydrated silica might have been less saline and only mildly acidic (Murchie *et al.,* 2009).

Potential visible, near-infrared, and mid-infrared orbital observations will clarify the relative merits of these sites to the extent that investigators can test the multiple hypotheses for the origins of aqueous mineral-bearing deposits. Such efforts will provide additional constraints on the habitability of their depositional environments. Any such insights would impact substantially the potential MAX-C site selection process. The potential future Trace Gas Mission (Smith *et al.,* 2009a) might also provide information of interest to the MAX-C mission concept, though MAX-C, as proposed in this report, would be focused on the search for signs of life in ancient rocks.

Also critically important is the extent to which geological deposits have preserved key information about the ancient habitable environment in which they formed. Fossilization processes are intimately tied to the physical, chemical, and biological conditions that accompany the formation and long-term persistence of geological deposits (Farmer and Des Marais, 1999). For example, chemically reducing conditions are better than oxidizing conditions in promoting the preservation of sedimentary organic matter. On Earth, minerals differ in their effectiveness as agents of preservation. Phyllosilicates and sulfates are excellent for preserving organic compounds and isotopic biosignatures, but they are less effective for preserving morphological fossils. Phyllosilicates can enhance the retention of organic compounds by binding molecules to charged mineral surfaces and incorporating them into mineral structures as interlayer cations (Keil *et al.,* 1994; Kennedy *et al.,* 2002; Wattel-Koekkoek *et al.,* 2003; Mayer, 2004). Silica and, to a lesser extent, carbonates can preserve all types of biosignatures. Microbial fossils can be preserved by entombment in fine-grained mineral precipitates, such as silica, phosphate, carbonate, or metallic oxides and sulfides. Sedimentary precipitates like silica and phosphate minerals can become very chemically stable and thus have very long residence times in Earth's crust. These minerals host the best-preserved microbial fossils in Earth's early geological record.

Orbital observations of the abundance and geological context of minerals such as these could support a prioritization of candidate MAX-C landing sites regarding their potential to have preserved an accessible record of ancient habitable environments. The numerous promising sites that have already been identified are widely distributed across a range of geographic locations and elevations. Further acquisition and analysis of orbiter data are needed to ensure a set of good choices for possible near-future landed missions.

MAJOR FINDING: An ongoing program of orbital observations would be essential to provide a robust site selection process for the proposed MAX-C mission.

9.1.2. Landers. Landers provide more-detailed and precise analyses of particular sites than is possible from orbital observations and make it possible to address questions such as: did environmental conditions at the site indeed favor habitability and preservation of a record? If so, are any organic compounds or other potential biosignatures present? If so, does the evidence indicate specifically that at least some chemical species, isotopic patterns, minerals, rock textures, or gaseous species probably originated from martian life and that an abiotic origin is unlikely?

The MSL mission is very well equipped to address these astrobiology questions as well as additional key objectives that address geological and climate history. Efforts by MSL to map the distribution of such minerals at various spatial scales will influence substantially the way phyllosilicates, sulfates, and silica are viewed as indicators of aqueous activity and habitability and as preservation media for biosignatures. The findings from MSL could, in turn, significantly impact potential future mission scientific objectives, the development of flight instruments needed for sample selection, and the choice of a specific landing site for potential sample return.

Given the care of the MSL site selection process and the great potential for MSL discoveries, the MSL site might become one of the finalists for the proposed MAX-C mission, though a potential sample return would have a wider range of scientific objectives than MSL. It is likely that discoveries from orbit would also provide compelling competing sites to the finalists. Selecting a new location would broaden the diversity of explored astrobiologically relevant environments by visiting a site that is both promising and qualitatively distinct from previously visited sites.

That said, MSL's substantial capabilities and its "front row seat" location on the ground will greatly enhance its prospects for achieving compelling discoveries (see Table 9.1). MSL should confirm, at a level of confidence unachievable from orbit, whether a habitable environment indeed existed at some time in the past and whether the depositional conditions favored good preservation of information about that environment. Mineral assemblages might indicate that fluids once existed and had water activities high enough to sustain active metabolism.

The Mars Science Laboratory might find *possible* evidence of prebiotic chemistry or life (Table 9.1). Organic materials could have molecular compositions that are either meteoritic or indigenous to Mars and could have had either an abiological or biological origin. MSL might find isotopically light carbon or sulfur in minerals or organic matter.

Even more compelling would be *probable* evidence of prebiotic chemistry or life. Examples include organic compounds that resemble microbial organic constituents on Earth or have compositions distinctly different from meteoritic materials. Microscale sedimentary fabrics and shapes also could suggest biological origins. Discrete cohesive organic layers might resemble the remains of microbial biofilms. Sedimentary fabrics might indicate stromatolites or microbialite-like structures. And patterns of stable isotopic abundances in combination with petrographic observations that indicate a biological origin would be highly significant.

One very specific hypothetical MSL mission scenario illustrates the case where the potential MAX-C site selection process might consider the MSL site *and* additional sites identified from orbit. For example, MSL finds well-preserved deposits from a past habitable environment, and these deposits contain organic matter of indeterminate origin(s). These findings would be *"possible evidence of life,"* but meteoritic organic compounds could not be excluded. In this scenario, the site would be designated a "finalist" for the proposed MAX-C mission, but if orbital observations have also identified other as yet unvisited localities that are highly promising, these would also be designated as finalists.

In another "possible evidence of life" hypothetical scenario, MSL explores a cross section of materials that orbital observations indicate were deposited in aqueous environments. The rover only reaches phyllosilicate deposits shortly before the end of the mission, and organic compounds of possible martian origin are finally discovered. Assessment of orbital imagery has revealed an even stronger connection between these types of phyllosilicates and long-lived liquid water on the martian surface. Such observations would warrant designating this as a potential "MAX-C finalist site."

Table 9.1. Examples of Significant Observations that Might Compel the Selection of a Site for the Proposed MAX-C Mission

	Observed by		
	Lander	*Orbiter*	
Example observations suggesting site was favorable in terms of habitability and/or preservation	x	x	(1) Minerals that indicate extended activity of liquid water
	x	x	(2) Minerals that indicate reducing conditions
	x	x	(3) Signs of early mineralization (favoring biosignature preservation)
	x	x	(4) Morphological features indicating aqueous transport and aqueous sedimentation
	x	x	(5) Evidence of a hydrothermal system
	x	x	(6) High diversity of deposits favorable for habitability (*e.g.*, phyllosilicates, silica, carbonates, sulfates)
	x	x	(7) Layered deposits with conspicuous lateral continuity
Example observations suggesting **possible** evidence of life or prebiotic chemistry	x		(1) Organic materials with molecular composition that could be meteoritic or indigenous with an abiological or biological origin
	x		(2) Isotopically light sulfur or carbon, etc., in minerals
Example observations suggesting **probable** evidence of life or prebiotic chemistry	x		(1) Organic materials with composition distinct from meteoritic organics
	x		(2) "Complex" organic material with overall composition similar to microbial organics on Earth
	x		(3) Ancient organic deposits with microbial mat-like characteristics (*e.g.*, cohesive, discrete layers)
	x		(4) Isotopic fractionation patterns with petrographic/petrologic observations suggesting primary, possibly biological origin
	x		(5) Stromatolitic or microbialite-like structures

Remote sensing observations can also have "possible evidence of life" scenarios. For example, a spacecraft corroborates the detection of atmospheric methane and demonstrates that higher methane concentrations appear to originate from a region that harbored ultramafic rocks, serpentine, and other evidence of aqueous alteration. Such a discovery might make this region a "finalist site."

A *"probable evidence of life"* scenario occurs if MSL confirms that the site has preserved a record of a past habitable environment and the spacecraft also discovers martian organic matter and possibly additional features for which martian life is the most probable source. Although such evidence might not yet provide proof of past martian life, it would provide a compelling argument that a potential sample return mission should go there in order to obtain potentially compelling evidence in Earth-based laboratories. In this scenario, the proposed MAX-C mission would likely be sent to the MSL site.

The MERs are still continuing their investigations, and one of them may yet encounter some new compelling deposits with chemical, mineralogical, and textural characteristics that compel us to make it a potential MAX-C "finalist site." The MER payload capabilities are limited compared to the MSL rover's, but we should leave open the possibility for new discoveries, as indicated in Fig. 9.1.

However, sending the proposed MAX-C mission to a previously visited site would reduce the range of geological environments visited. Mars exploration resources would be concentrated at a single site, which would thereby potentially reduce (or at least slow) our efforts to better understand global martian geological diversity of habitable environments. Finally, a requirement to return to a previous site would preclude a potential sample return mission from visiting a compelling new site identified from orbit after the proposed MAX-C mission (though it is likely that a sufficiently compelling observation would lead to a change in the requirement).

9.2. Selection of a landing site of high potential interest

The site visited by a potential sample return mission should contain samples of high relevance to the life question, and a MAX-C site selection competition would provide an opportunity to evaluate candidates. Over the past 35 years, the Mars program has successfully visited six landing sites. However, three of those sites (Viking 1 and 2, and Pathfinder) are clearly not of broad enough interest to justify an astrobiology-focused MSR mission. The Phoenix site is likely not accessible to the potential sample return flight system and in any case would probably not be judged to be scientifically compelling from a "signs of life" viewpoint. Both of the MERs have encountered and documented past geological environments that are potentially habitable and thus hold interest for sample return. The two MERs are still operating and could yield new discoveries that might make one of their landing sites more enticing for sample return. Thus, two of six past sites are possible candidates for a potential astrobiology-focused sample return mission. However, with the recent improvement in our knowledge of martian surface geology (notably from the Mars Reconnaissance Orbiter, MRO), there is a consensus that, from the perspective of potential sample return, more promising sites than these almost certainly exist.

FINDING: There are many candidate sites of high interest for a potential sample return beyond those previously visited or to be visited by MSL.

As our knowledge of the martian surface has increased, there has been a parallel increase in the number and nature of sites that have the potential to contain outstanding samples for a possible sample return. In the area of astrobiology, the NRC (2007) recently listed some of the high-interest sites. In addition, at recent Mars-related conferences (*e.g.*, Lunar and Planetary Science Conference, European Planetary Science Congress, the American Geophysical Union, 7^{th} International Conference on Mars, European Geosciences Union), the global Mars scientific community has developed multiple additional site-specific astrobiology hypotheses, the testing of which could substantially address the life question. The four candidate MSL landing sites still under consideration as of this writing are also of interest from an astrobiological perspective. However, sample return scientific objectives go beyond astrobiology and habitability. For example, as recently discussed at the conference "Ground Truth from Mars: Science Payoff from a Sample Return Mission" (April 21–23, 2008, Albuquerque, New Mexico, http://www.lpi.usra.edu/meetings/msr2008/), other kinds of geological materials of interest include sulfate minerals (which may contain a record of Mars near-surface processes), igneous rocks (which are fundamental to understanding the martian interior), hydrous minerals (which may contain a record of fluid-atmospheric evolution and secondary alteration), a full spectrum of sedimentary rocks, samples that represent a depth profile, and others.

As with all landed missions to Mars, the best way to evaluate the multiple sample return landing site possibilities, priorities, and advocacy positions is through an open competitive landing site selection process. Developing a consensus for a potential sample return landing site would be essential for generating a broad, politically valuable support base. The proposed MAX-C mission represents the first opportunity to hold an open, competitive selection process to identify a landing site with consideration of potential sample return criteria.

FINDING: The landing site selection process for a potential sample return mission should start as soon as possible to take full advantage of the currently orbiting high-resolution instruments.

It is extremely important that a broad spectrum of landing site possibilities be available for this landing site competition. Recent results from orbital missions, highlighted by those from MRO, indicate that many candidate landing sites for the proposed MAX-C mission will likely be located in the ancient terrains of the Southern Highlands, where the record of aqueous alteration and processes is best preserved and exposed. Experience with the MSL and previous landing site selection activities has shown that a range of candidate MAX-C sites should be available for exploration if elevations up to +1 km could be accessed, but restriction to progressively lower elevation would result in loss of a rapidly increasing number of attractive sites (see Fig. 9.2).

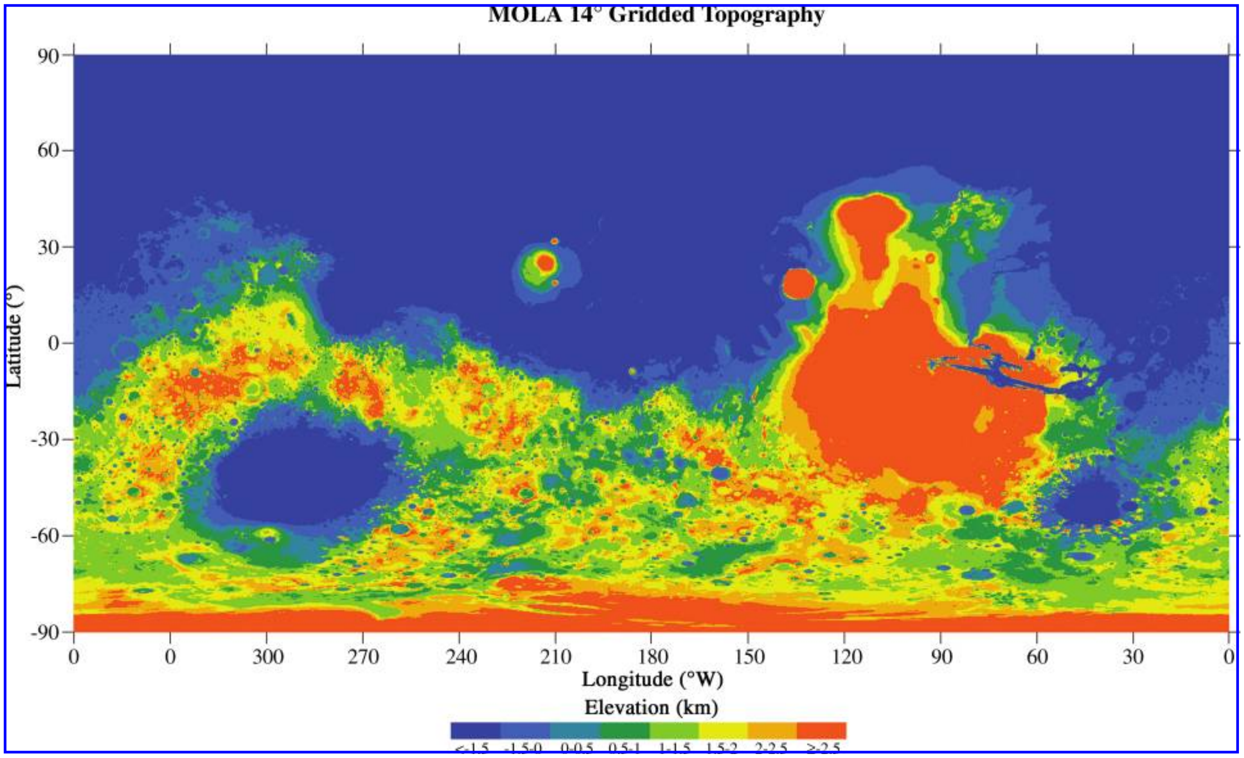

FIG. 9.2. Mercator projection of ¼ gridded Mars Orbiter Laser Altimeter (MOLA) topography of Mars from 90°S to 90°N latitude, showing the areas below +1 km elevation in blue and dark green. Elevation is relative to the MOLA datum (Smith *et al.,* 2001). This map uses an areocentric coordinate convention with west longitude positive. Image Credit: NASA/JPL-Caltech/GSFC.

FINDING: A significant number of candidate landing sites, of high relevance to the objectives of the proposed MAX-C mission, with elevations less than +1 km MOLA datum are known. It is very important for this proposed mission to preserve the option of accessing the Southern Highlands, for which this threshold is a practical minimum.

10. Some Engineering Considerations Related to the Consensus Mission Vision

10.1. Solar power and thermal considerations

The proposed architecture would use solar arrays to power the rover. This would drive the power and thermal design and would result in a practical limit to latitude access for the mission. The desired mission duration of at least 1 Earth year (half a Mars year) and the season at landing would result in a requirement to be able to operate in nearly any seasonal extreme. In northern latitudes it would be winter at arrival and summer at the end of the mission. The opposite seasons are experienced for southern landing sites. Due to the eccentricity of the martian orbit, northern latitudes are less severe on the power/thermal design than southern latitudes, which would allow effective operation at sites as far north as 25°N and as far south as 15°S.

10.2. Entry, descent, and landing, and rover traverse capabilities

The performance of the EDL system is an important factor in defining the accessible landing sites on Mars and in sizing some key rover attributes. The major EDL performance attributes relevant to this discussion are delivered mass, landing altitude, and landing ellipse size. In general, less mass can be delivered to a higher altitude, more mass to a lower altitude, but there are limits to this trade due to other engineering constraints (*e.g.,* structural design, guidance and control considerations). The size of the landing ellipse is in part dependent upon EDL phase ***a priori*** attitude knowledge errors that propagate through the entry phase. The ellipse can be tightened up incrementally by tightening up the knowledge errors. Landing ellipse size is primarily of interest when improved access to specific features on Mars is to be considered. Given that scientifically interesting features often represent terrain that is too dangerous on which to land, the landing ellipse is often driven to be placed right up against, but not on top of, features of interest. The result is that access is often a product of both ellipse size and traverse capability that is sufficient to get outside of that ellipse in a reasonable amount of time relative to the mission lifetime.

The mass of the proposed MAX-C rover is estimated to be in a mass class much smaller than MSL but larger than the MERs. This makes a reflight of the MSL Cruise/EDL system the prudent choice to deliver the proposed MAX-C rover to the surface of Mars. The proposed MAX-C mission would arrive at Mars in January of 2019 at an $L_s = 325°$ (northern midwinter). Given the favorable atmospheric pressure at this time of the martian year, performance of the MSL delivery system could possibly allow altitudes up to +1 km, depending upon the final landed mass. There are also unfavorable effects on the atmosphere from possible dust storms, and the combination of all of this has not been fully evaluated at this time. The landing ellipse size could be reduced from the MSL 10 km radius capability to as small as 7 km (Wolf and Ivanov, 2008). A traverse capability complementary to this would be provided to allow access outside of the landing ellipse.

To achieve the scientific objectives, it would be important for the rover to have sufficient ability to apply its payload to particular features of interest (outcrops, layers, etc.). The proposed rover would have a mobility system physically similar to that of the MERs, only slightly larger. The traverse capabilities of the MERs are seen as the standard for such feature access. The key parameters behind a rover's ability to traverse slopes, sandy terrain, and rock fields are as follows:

- Ground Pressure: Defined as the ratio of the weight of the vehicle to the effective contact patch of its wheels. Ground pressure for the proposed MAX-C rover would be as good as, or better than, that of the MERs, which would allow safe and effective traverse on loose or sandy slopes of as high as 10–12 degrees.
- Static Stability Angle: Defined as the complement of the angle from the ground up to the rover center of mass, measured from the various outer edges and pivot points of the rover suspension. The proposed MAX-C rover would be designed with a sufficiently high static stability angle to allow safe and effective traverse on well-consolidated or rock-plated terrain up to $\sim$30 degrees.
- Wheel Size and Belly Clearance: The diameter of the wheels and the distance from the belly of the rover to the ground defines the size of rock that is deemed an obstacle. The proposed MAX-C rover would be designed to be at least as large as the MERs in these parameters, which would allow effective traverse in rock fields at least as dense as encountered by the MERs.

Another important capability for accessing features of interest is traverse rate (or effective daily average rate). In some landing sites, it might be desired to traverse distances as far as 10 km to reach the features of interest. Given the modest lifetime of 1 Earth year suggested for the proposed MAX-C mission, the necessary traverse rate for the rover would need to be improved over past experience. It is estimated that a factor of 2–3 improvement over the actual MER capability could be required. Through the use of improved algorithms and hardware for navigation functions, it could be possible to increase the traverse rate for the proposed MAX-C rover by at least this much.

The MSL landing system (called "sky crane") would likely be used for the proposed MAX-C mission and would result in similar engineering constraints on the landing ellipse (to first order) as those applied to MSL. By analogy with the MSL landing site selection process, many of the highest-priority landing locations identified from orbit cannot be directly accessed and might require the ability to traverse beyond the perimeter of the landing ellipse. Although good

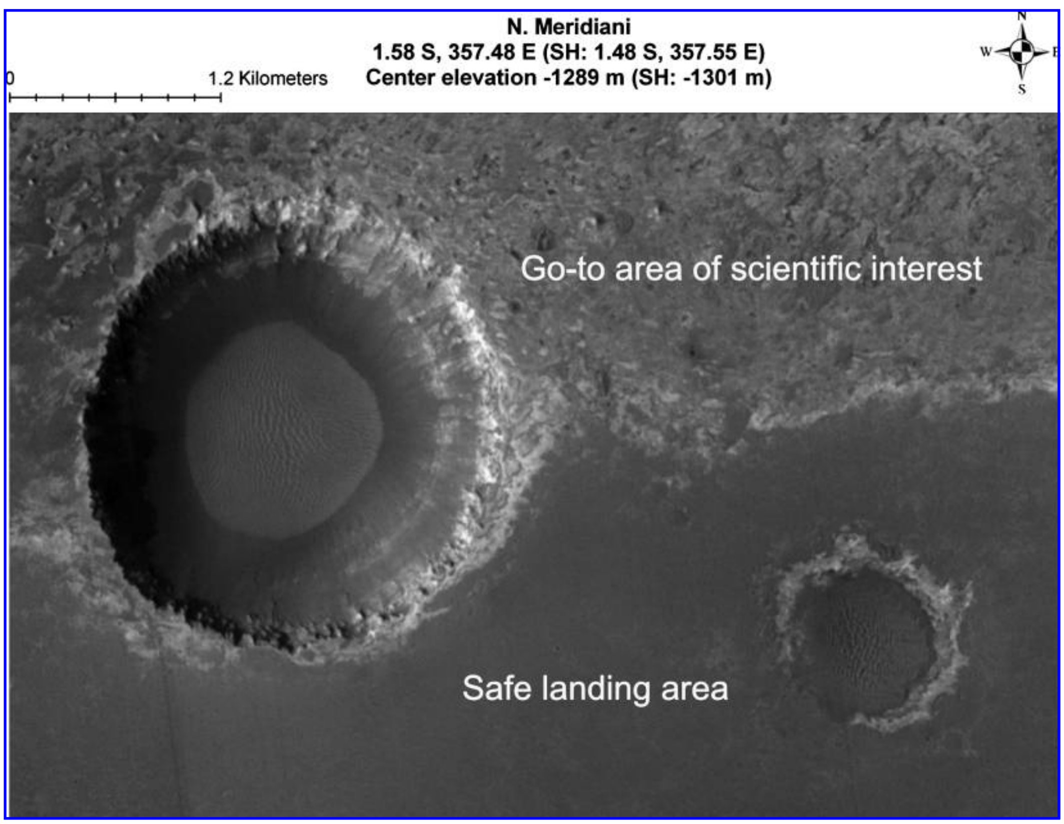

FIG. 10.1. An example of a "go to" landing site that would be well suited for landing in the smooth safe area to the south but then requiring a possibly long rover drive to get to the area of scientific interest on rougher terrain. Mosaic of CTX images P05_003168_1825 and P06_003379_1827 shows a portion of a Northern Meridiani site that is no longer being considered for MSL. Image credit: NASA/JPL-Caltech/MSSS.

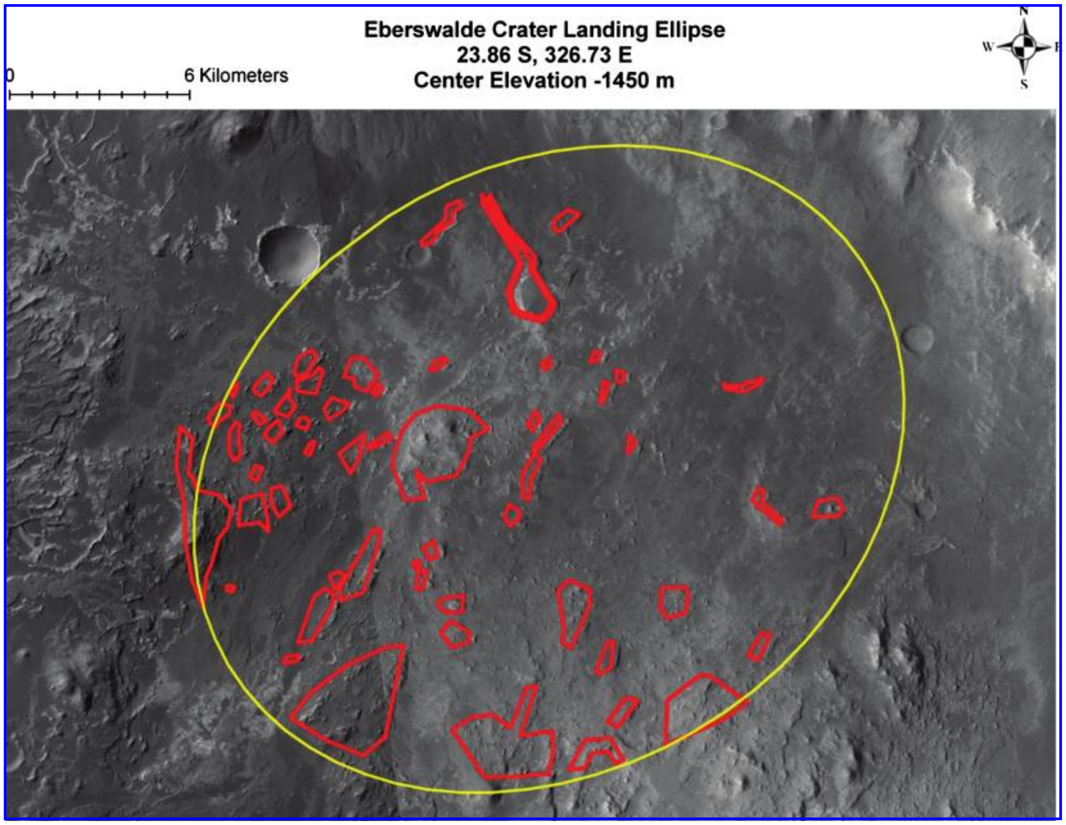

FIG. 10.2. An example of a landing site that could benefit from hazard avoidance during descent to avoid the rough terrain outlined by red polygons. Mosaic of CTX images P01_001336_1560 and P06_003222_1561, showing the ellipse for the Eberswalde candidate MSL landing site. Image credit: NASA/JPL-Caltech/MSSS, polygons generated by Eldar Noe Dobrea and Matthew Golombek.

scientific targets exist within all the final candidate sites for MSL, primary scientific targets are near the edge or outside the ellipse for three of the final four candidate sites selected. Figure 10.1 shows an example of a "go to" type of landing site. Outcrop access would be essential to the scientific return of the MAX-C mission concept. Areas of extensive outcrop are typically associated with significant topography, which correlates to landing hazard for an MSL landing system. An alternative would be to land in a place where it is topographically rough but the landing ellipse contains all the targets of interest, and use hazard avoidance technology (Mourikis *et al.*, 2009) during descent to land on a safe spot (see Fig. 10.2 for an example of this kind of landing).

FINDING: The proposed MAX-C mission would require either (a) the ability to traverse beyond the landing ellipse to targets of interest or (b) hazard avoidance capability during EDL and an ability to traverse to targets of interest within the ellipse.

The use of hazard avoidance would reduce rover mobility requirements and the risk of a surface rendezvous with a potential sample return "fetch" rover. However, if hazard avoidance is not possible due to risk or cost reasons, an increased rover traverse capability could be relied on.

The capability to navigate on slopes of up to 30 degrees, as both of the MERs have done, would be extremely useful for the proposed MAX-C mission. Many of the geologically interesting terrains on Mars expose stratified layers on slopes in craters, channels, and hillsides. Access to these kinds of slopes would allow the proposed MAX-C mission to characterize a sequence of layers and lower the risk to achieving the scientific objectives. Limiting this capability could rule out certain landing sites, could cause a rover to take a much longer path to get to a target of interest, or could preclude access to certain targets of interest. Also, another consequence of limiting the slope capability is that it would increase the rover egress challenges for those architectures that include a landing pallet. Less slope capability means that smaller rocks become landing hazards. The ability to also acquire cores for the proposed cache while the rover is parked on a slope is also highly desirable, though this should be part of a future science/engineering trade study.

10.3. Sample acquisition, mechanical handling, and caching

10.3.1. Abrading. Abrading of surface material would be accomplished through the use of a specialized abrading bit placed in the coring tool (Zacny *et al.*, 2008). The incremental mass and complexity of this approach, given the existence of the coring tool with bit change-out capability, is small (much smaller than adding a separate abrading tool). This tool would be intended to remove small amounts of surface material to allow instruments access past any dust or weathering layer. It would abrade a circular area of similar diameter to the core (8–10 mm). Translation of the arm would be used to scan or mosaic the individual abrasion spots to expose larger areas. Design parameters would be explored to strike a balance between the engineering desire to use percussion for efficient abrading and the scientific desire to have a smooth cut surface to observe. The surface contamination due to abrasion would need to be constrained so as not to interfere with organic compound detection, if such an instrument is included in the payload.

10.3.2. Coring. Coring would be accomplished through the use of a coring tool on a 5-degree-of-freedom arm, to allow acquisition from a diverse set of targets. It could produce cores of approximately 10 mm diameter up to 50 mm long, which would be encapsulated in individual sleeves with pressed-in caps. The system would minimize mechanical handling of the cored material through a design that allows core acquisition to take place directly into the encapsulation sleeve. Bit change-out capability would also be provided to allow for bit wear, breakage, and loss of any kind.

Cores could be made available for observation through a mechanism to allow placing them on an observation tray at the front of the rover. In this tray, they would be accessible or visible by instruments on both the arm and mast. Cores placed in the tray could not later be encapsulated for placement in the cache. Once placed in the tray, and subsequent to any interrogations by mast or arm-mounted instruments, cores would be discarded.

The nature of the coring tool would be rotary percussive [like a common hammer drill, see Stanley *et al.* (2007) for an example]. It does not cut the rock but rather fractures and pulverizes it in the impact patch (the circumference of the core). This percussive action results in minimal temperature rise of the actual core, especially across the multi-hour extraction process, but produces a slightly rougher surface than a pure cutting tool would.

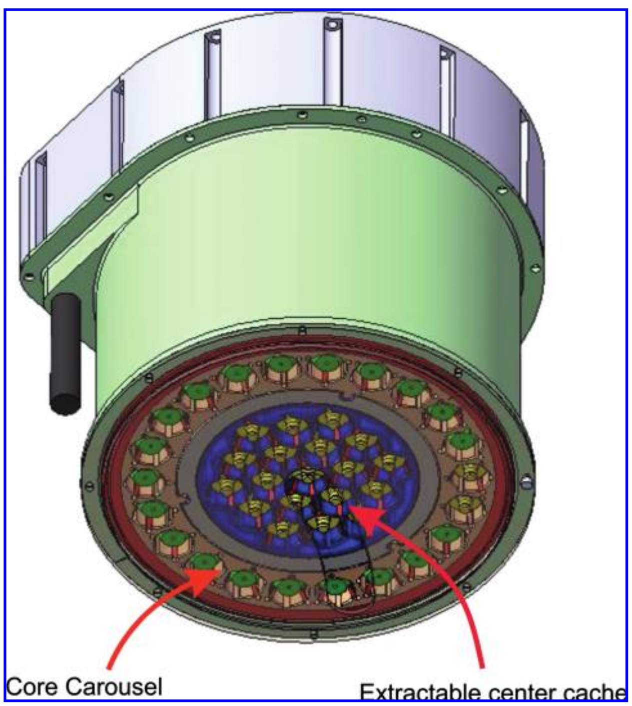

FIG. 10.3. Schematic showing a possible design for a carousel to hold sleeved rock cores. The center cache is removable.

10.3.3. Caching. The rover would be equipped with a mechanism for handling cores, capping their individual sleeves, and retaining them in a hexagonal packed cylinder [Fig. 10.3 shows one example of how a cache could be configured. See Collins *et al.* (2009)]. The coring bit (with sleeved core inside) would be released into the handling system as part of the transfer mechanism for each core. Bit change-out essentially would occur during transfer of every cached core, which would make it advantageous to combine the more general spare bit change-out function in the same system. The sleeved core would be retrieved from the bit, capped, and placed into the cache. Specification of the exact size of the cache would be the subject of future trade-off studies, but it appears it would be feasible to incorporate a cache of 20–30 cores, plus some extra sleeves/caps to allow for swap-out or loss for whatever reason. The proposed MAX-C rover could be designed to place the cache on the surface of Mars at a location favorable for subsequent retrieval by a rover from a potential future mission or to retain the cache for retrieval directly from the proposed MAX-C rover.

The entire core handling and caching assembly would be enclosed and sealed with the only entry point being a small port where the bit (with sleeved core inside) would be inserted for transfer. The bit port would be covered and oriented facing down so nothing could fall into it. This is all favorable for planetary protection and contamination control, which would impose rigorous requirements on this mission in order to produce a cache that would be valid for return to Earth (see MEPAG MRR-SAG, 2009).

The capability for the proposed MAX-C rover to drop off the sample cache at a location favorable for retrieval by a subsequent mission could make it much easier for a potential "fetch" rover to access quickly. Once the cache is dropped off, the proposed MAX-C rover could go into more rugged terrain for its own *in situ* science without increasing the risk to a potential sample return. This would benefit the analysis of potential returned samples by expanding the regional context of those collected samples.

10.4. Overall risk and cost issues

The implementation described above would rely on significant inheritance of MSL cruise and EDL spacecraft designs to minimize cost and risk. Using an MSL design for cruise stage, entry body, and sky-crane landing system would be the proposed approach. This would result in substantive inheritance from MSL in the flight design, test design, and test and handling hardware. The intermediate scale of the proposed rover would drive a new mechanical and thermal development. The basis for the design would be well understood since it could draw upon the experience of MER and MSL. At the component level, the proposed rover would draw heavily upon MSL heritage. The result would represent a medium risk and medium cost for the rover.

A typical development schedule for this kind of project would be approximately 6 years, Phase A through D, plus some advanced technology development activities in the years preceding that. Based on this schedule and a full JPL Team X estimate, the MRR-SAG's cost estimate is in the range of 1.5–2.0 billion, real-year dollars for a possible launch in 2018. The operations phase after launch plus 30 days is not included in this estimate. The estimate does include a baseline Atlas V 531 launch service at an estimated cost of ~$290 million. Also included is ~$70 million in technology development activities to address the needs described in the next section, with the exception of instrument technology. It is assumed that key instrument technologies would be advanced as needed through other funding sources (*i.e.*, MIDP or other such activity) to an appropriate readiness level to respond to an Announcement of Opportunity, from which point the remaining development cost would be provided by the project. For the entire estimate, cost reserves of 30% on top of the base estimate are also included.

10.5. Summary of potential MAX-C technology development needs

Several key technologies would need further development (Hayati *et al.*, 2009) to support the mission concept. These include technologies in five areas:

- Coring, encapsulation, and caching: Lightweight tools/mechanisms would be needed to obtain and handle cored material.
- Instruments: Additional technology focus should be applied to instruments that could address the measurement needs posed herein, particularly the microscale mineralogy, organic compounds, and elemental composition mapping.
- Planetary protection/contamination control: Biocleaning, cataloguing of biocontaminants, and transport modeling to ensure cached samples would be returnable.
- Rover navigation: Onboard image processing and navigation to increase traverse rate.
- Entry, descent, and landing: Precision landing and hazard avoidance.

10.6. A programmatic note

The proposed MAX-C mission concept has been studied by the MRR-SAG since April, 2009. The strategy has been to develop the most cost-effective concept to meet the *in situ* scientific and caching objectives. The resulting proposed rover would be in a mass class much smaller than MSL but larger than MER. This makes an MSL Cruise/EDL system the prudent choice to deliver the proposed MAX-C rover to the surface of Mars. Recent high-level discussions between NASA and ESA have led to the possibility of delivering the ESA ExoMars rover and the proposed NASA MAX-C rover to Mars together in 2018 on a single launch vehicle with the MSL EDL system. This combined mission concept has been explored only briefly thus far. The implementation discussion in this report reflects a proposed NASA-only MAX-C mission, but the general capabilities for the proposed MAX-C mission would be expected to be similar for a dual mission architecture.

11. Acknowledgments

We are grateful to these outside experts who assisted our team in answering questions: Fernando Abilleira, F. Scott Anderson, Paul Backes, Don Banfield, Luther Beegle, Rohit Bhartia, Jordana Blacksberg, Diana Blaney, Karen Buxbaum, Shane Byrne, John Eiler, Sabrina Feldman, Lori Fenton, Kathryn Fishbaugh, Marc Fries, Matt Golombek, Bob Haberle, Samad Hayati, Michael Hecht, Arthur (Lonne) Lane, Lucia Marinangeli, Richard Mattingly, Tim Michaels, Denis Moura, Zacos Mouroulis, Mike Mumma, Scot Rafkin, Carol Raymond, Glenn Sellar, Christophe Sotin, Rob Sullivan, Tim Swindle, Marguerite Syvertson, Ken Tanaka, Peter Thomas, Lawrence A. Wade, Ben Weiss, Richard Zurek, and the MEPAG Goals Committee. Some of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. In the early parts of this study, the contributions of Hap McSween were important.

12. Abbreviations

APXS, Alpha Particle X-Ray Spectrometer
DUV, deep ultraviolet
EDL, entry, descent, and landing
JPL, Jet Propulsion Laboratory
MATT, Mars Architecture Tiger Team
MAV, Mars Ascent Vehicle
MAX-C, the Mars Astrobiology Explorer-Cacher
MEPAG, Mars Exploration Program Analysis Group
MER, Mars Exploration Rover
MIDP, Mars Instrument Development Program
MOLA, Mars Orbiter Laser Altimeter
MRO, Mars Reconnaissance Orbiter
MRR, Mid-Range Rover
MRR-SAG, Mid-Range Rover Science Analysis Group
MSL, Mars Science Laboratory
MSR, Mars Sample Return
ND-SAG, Next Decade Science Analysis Group
NRC, National Research Council
PIDDP, Planetary Instrument Definition and Development Program
RAT, Rock Abrasion Tool
S/N, signal-to-noise ratio
TRL, Technology Readiness Level
XRF, X-ray fluorescence

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Submitted 2 December 2009
Accepted 6 January 2010