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The potential science and engineering value of samples delivered to Earth by Mars sample return

International MSR Objectives and Samples Team (iMOST)

D. W. BEATY, M. M. GRADY, H. Y. McSWEEN, E. SEFTON-NASH, B. L. CARRIER, F. ALTIERI, Y. AMELIN, E. AMMANNITO, M. ANAND, L. G. BENNING, J. L. BISHOP, L. E. BORG, D. BOUCHER, J. R. BRUCATO, H. BUSEMANN, K. A. CAMPBELL, A. D. CZAJA, V. DEBAILLE, D. J. DES MARAIS, M. DIXON, B. L. EHLMANN, J. D. FARMER, D. C. FERNANDEZ-REMOLAR, J. FILIBERTO, J. FOGARTY, D. P. GLAVIN, Y. S. GOREVA, L. J. HALLIS, A. D. HARRINGTON, E. M. HAUSRATH, C. D. K. HERD, B. HORGAN, M. HUMAYUN, T. KLEINE, J. KLEINHENZ, R. MACKELPRANG, N. MANGOLD, L. E. MAYHEW, J. T. McCOY, F. M. McCUBBIN, S. M. McLENNAN, D. E. MOSER, F. MOYNIER, J. F. MUSTARD, P. B. NILES, G. G. ORI, F. RAULIN, P. RETTBERG, M. A. RUCKER, N. SCHMITZ, S. P. SCHWENZER, M. A. SEPHTON, R. SHAHEEN, Z. D. SHARP, D. L. SHUSTER, S. SILJESTRÖM, C. L. SMITH, J. A. SPRY, A. STEELE, T. D. SWINDLE, I. L. TEN KATE, N. J. TOSCA, T. USUI, M. J. VAN KRANENDONK, M. WADHWA, B. P. WEISS, S. C. WERNER, F. WESTALL, R. M. WHEELER, J. ZIPFEL, and M. P. ZORZANO

Final Report

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This report requested by the International Mars Exploration Working Group (IMEWG).

Questions or requests for follow-up information should be sent to David Beaty (dwbeaty@jpl.nasa.gov, 818-354-7968), Monica Grady (monica.grady@open.ac.uk), Hap McSween (Mcsween@utk.edu), Elliot Sefton-Nash (esefton@cosmos.esa.int), or Brandi Carrier (Brandi.L.Carrier@jpl.nasa.gov).

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EXECUTIVE SUMMARY

Return of samples from the surface of Mars has been a goal of the international Mars science community for many years. Affirmation by NASA and ESA of the importance of Mars exploration led the agencies to establish the international MSR Objectives and Samples Team (iMOST). The purpose of the team is to re-evaluate and update the sample-related science and engineering *objectives* of a Mars Sample Return (MSR) campaign. The iMOST team has also undertaken to define the *measurements* and the *types of samples* that can best address the objectives.

Seven objectives have been defined for MSR, traceable through two decades of previously published international priorities. The first two objectives are further divided into sub-objectives. Within the main part of the report, the importance to science and/or engineering of each objective is described, critical measurements that would address the objectives are specified, and the kinds of samples that would be most likely to carry key information are identified. These seven objectives provide a framework for demonstrating how the first set of returned Martian samples would impact future Martian science and exploration. They also have implications for how analogous investigations might be conducted for samples returned by future missions from other solar system bodies, especially those that may harbor biologically relevant or sensitive material, such as Ocean Worlds (Europa, Enceladus, Titan) and others.

SUMMARY OF OBJECTIVES AND SUB-OBJECTIVES FOR MSR IDENTIFIED BY IMOST

Objective 1: Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.

Intent: To investigate the geologic environment(s) represented at the Mars 2020 landing site, provide definitive geologic context for collected samples, and detail any characteristics that might relate to past biologic processes.

This objective is divided into five sub-objectives that would apply at different landing sites.

1.1. *Characterize the essential stratigraphic, sedimentologic, and facies variations of a sequence of Martian sedimentary rocks.*

Intent: To understand the preserved Martian sedimentary record.

Samples: A suite of sedimentary rocks that span the range of variation.

Importance: Basic inputs into the history of water, climate change, and the possibility of life.

1.2. *Understand an ancient Martian hydrothermal system through study of its mineralization products and morphological expression.*

Intent: To evaluate at least one potentially life-bearing "habitable" environment

Samples: A suite of rocks formed and/or altered by hydrothermal fluids.

Importance: Identification of a potentially habitable geochemical environment with high preservation potential.

1.3. *Understand the rocks and minerals representative of a deep subsurface groundwater environment.*

Intent: To evaluate definitively the role of water in the subsurface.

Samples: Suites of rocks/veins representing water/rock interaction in the subsurface.

Importance: May constitute the longest-lived habitable environments and a key to the hydrologic cycle.

1.4. *Understand water/rock/atmosphere interactions at the Martian surface and how they have changed with time.*

Intent: To constrain time-variable factors necessary to preserve records of microbial life.

Samples: Regolith, paleosols, and evaporites.

Importance: Subaerial near-surface processes could support and preserve microbial life.

1.5. *Determine the petrogenesis of Martian igneous rocks in time and space.*

Intent: To provide definitive characterization of igneous rocks on Mars.

Samples: Diverse suites of ancient igneous rocks.

Importance: Thermochemical record of the planet and nature of the interior.

Objective 2: Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.

Intent: To investigate the nature and extent of Martian habitability, the conditions and processes that supported or challenged life, how different environments might have influenced the preservation of biosignatures and created nonbiological "mimics," and to look for biosignatures of past or present life

This objective has three sub-objectives:

2.1. *Assess and characterize carbon, including possible organic and pre-biotic chemistry.*

Samples: All samples collected as part of Objective 1.
Importance: Any biologic molecular scaffolding on Mars would likely be carbon-based.

2.2. *Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.*
Samples: All samples collected as part of Objective 1.
Importance: Provides the means of discovering ancient life.

2.3. *Assess the possibility that any life forms detected are alive, or were recently alive.*
Samples: All samples collected as part of Objective 1.
Importance: Planetary protection, and arguably the most important scientific discovery possible.

Objective 3: Quantitatively determine the evolutionary timeline of Mars.
Intent: To provide a radioisotope-based time scale for major events, including magmatic, tectonic, fluvial, and impact events, and the formation of major sedimentary deposits and geomorphological features.
Samples: Ancient igneous rocks that bound critical stratigraphic intervals or correlate with crater-dated surfaces.
Importance: Quantification of Martian geologic history.

Objective 4: Constrain the inventory of Martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.
Intent: To recognize and quantify the major roles that volatiles (in the atmosphere and in the hydrosphere) play in martian geologic and possibly biologic evolution
Samples: Current atmospheric gas, ancient atmospheric gas trapped in older rocks, and minerals that equilibrated with the ancient atmosphere.
Importance: Key to understanding climate and environmental evolution.

Objective 5: Reconstruct the processes that have affected the origin and modification of the interior, including the crust, mantle, core and the evolution of the martian dynamo.
Intent: To quantify processes that have shaped the planet's crust and underlying structure, including planetary differentiation, core segregation and state of the magnetic dynamo, and cratering.
Samples: Igneous, potentially magnetized rocks (both igneous and sedimentary) and impact-generated samples.
Importance: Elucidate fundamental processes for comparative planetology.

Objective 6: Understand and quantify the potential Martian environmental hazards to future human exploration and the terrestrial biosphere.
Intent: To define and mitigate an array of health risks related to the Martian environment associated with the potential future human exploration of Mars.
Samples: Fine-grained dust and regolith samples.
Importance: Key input to planetary protection planning and astronaut health.

Objective 7: Evaluate the type and distribution of in situ resources to support potential future Mars exploration.
Intent: To quantify the potential for obtaining Martian resources, including use of Martian materials as a source of water for human consumption, fuel production, building fabrication, and agriculture.
Samples: Regolith.
Importance: Production of simulants that will facilitate long-term human presence on Mars.

SUMMARY OF iMOST FINDINGS

Several specific findings were identified during the iMOST study. While they are not explicit recommendations, we suggest that they should serve as guidelines for future decision making regarding planning of potential future MSR missions.

1. The samples to be collected by the Mars 2020 (M-2020) rover will be of sufficient size and quality to address and solve a wide variety of scientific questions.
2. Samples, by definition, are a statistical representation of a larger entity. Our ability to interpret the source geologic units and processes by studying sample sub sets is highly dependent on the quality of the sample context. In the case of the M-2020 samples, the context is expected to be excellent, and at multiple scales. (A) Regional and planetary context will be established by the on-going work of the multi-agency fleet of Mars orbiters. (B) Local context will be established at

field area- to outcrop- to hand sample- to hand lens scale using the instruments carried by M-2020.
3. A significant fraction of the value of the MSR sample collection would come from its organization into sample suites, which are small groupings of samples designed to represent key aspects of geologic or geochemical variation.
4. If the Mars 2020 rover acquires a scientifically well-chosen set of samples, with sufficient geological diversity, and if those samples were returned to Earth, then major progress can be expected on all seven of the objectives proposed in this study, regardless of the final choice of landing site. The specifics of which parts of Objective 1 could be achieved would be different at each of the final three candidate landing sites, but some combination of critically important progress could be made at any of them.
5. An aspect of the search for evidence of life is that we do not know in advance how evidence for Martian life would be preserved in the geologic record. In order for the returned samples to be most useful for both understanding geologic processes (Objective 1) and the search for life (Objective 2), the sample collection should contain BOTH typical and unusual samples from the rock units explored. This consideration should be incorporated into sample selection and the design of the suites.
6. The retrieval missions of a MSR campaign should (1) minimize stray magnetic fields to which the samples would be exposed and carry a magnetic witness plate to record exposure, (2) collect and return atmospheric gas sample(s), and (3) collect additional dust and/or regolith sample mass if possible.

I. INTRODUCTION

Return of samples from the surface of Mars has been a goal of the international Mars exploration community for many years. Strategies for the collection of such samples have ranged from "grab and go" acquisition from the surface, to dust collection in the atmosphere, to scientific selection from geologically capable rovers. As comprehension of the complexity and potential habitability of Mars has increased, so has the realization that a randomly collected sample, while potentially interesting, would not be sufficient to answer the really big questions that for years have motivated Mars surface sample return. The deployment of NASA's Mars 2020 (M-2020) sample-collecting rover has brought the issues associated with the completion of Mars Sample Return into sharp focus. M-2020 will collect and cache geological samples for possible eventual return to Earth. The transportation to Earth would need to involve a sample-retrieval mission, which could also collect atmospheric samples, and an Earth return mission. Involvement of the international community in these potential missions would be very beneficial in terms of sharing cost, risk, and benefit on an international basis.

i.1 This Study

In 2017, the space exploration programs associated with the International Mars Exploration Working Group (IMEWG) began discussion of a formal program of cooperation and collaboration related to Mars sample return (MSR). An important question is whether the space-faring nations will form a partnership to fly the missions needed to retrieve the samples, to transport them back to Earth, and to set in motion the planning processes associated with the curation and study of the samples once they arrive. As one input to this, the International MSR Objectives and Samples Team (iMOST) was chartered (Appendix 1) in November 2017 by the International Mars Exploration Working Group (IMEWG) to address certain key science planning questions.

The purpose of this study was to update the scientific value of MSR, given the now-known realities of the M-2020 sampling system, the incremental discoveries from Mars that have been made since the last big MSR study, and evolving priorities in astrobiology, geology, and geochemistry. Is MSR as important as it once was? How can the scientific objectives of MSR best be organized? What kinds of samples are needed to achieve those objectives? As input to planning what would happen if the samples arrived on Earth, which measurements on those samples would be implied by the MSR scientific objectives? Although the possibility of returning a second set of samples at some point in the more distant future exists, and is an interesting discussion, we have limited the scope of this report to evaluating scientific and engineering objectives that would justify return of the M-2020 samples.

i.1.1 Structure of this Report

The seven proposed objectives for Mars Sample Return are listed in Table i.1. The following seven chapters discuss each of the objectives (and, for Objectives 1 and 2, each of the associated sub-objectives) in detail. For each, we have presented an introduction and assessment of the current state of knowledge, an analysis of key open questions, and discussion of why returned sample analysis is important for addressing these open questions. Each proposed objective has been decomposed into a set of component investigation strategies, and for each of those the samples needed to carry out the strategy are identified, as well as the measurements that would logically need to be made on those samples. It is assumed that samples would be selected using the best available contextual data available to the M-2020 team. The measurements listed do not necessarily encompass all possible measurements that could be made on each sample, but include the most important measurements identified by the iMOST team to advance each Investigation Strategy. Prioritization only exists in these sections where explicitly stated. The Discussion section compiles the diversity of sample types described in the technical sections of the report, and discusses some possibilities for follow-up studies. Appendices include the Terms of Reference for this study, a glossary of key technical terms, a glossary of acronyms, a list of the authors of this report and their affiliations, and a description of the expected size and quality of the samples to be collected by Mars 2020.

i.2 Purpose and Intended Uses of this Report

In preparing this report, we have developed an understanding of the multiple dimensions of the potential scientific value of Mars samples if they were returned to Earth. Our intent is to convey this information in support of the following:

1. Planning: The planning processes for the potential MSR retrieval and transportation missions. We have updated as specifically as possible our understanding of the scientific and engineering value of the M-2020 samples if they were returned to Earth, to assess whether or not their value justifies the cost. The Mars 2020 sample-caching rover mission is the first essential component of an MSR campaign. Its existence constitutes a critical opportunity—the possibility of completing MSR is more real now than it has ever been.
2. Sample Acquisition: Some of the scientific objectives of MSR require certain types of samples, or sample suites that are designed in a specific way. Our intent is to convey the relationships between samples and objectives to the science team operating the M-2020 rover, for their use as they plan the operations and

Table i.1. Summary of the proposed sample-related objectives for MSR.

Proposed Objectives		
	Shorthand	**Full Statement of Objective**
Objective 1	***Geological environment(s)***	Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.
Sub-Obj. 1.1	***Sedimentary system***	Characterize the essential stratigraphic, sedimentologic, and facies variation of a sequence of Martian sedimentary rocks.
Sub-Obj. 1.2	***Hydrothermal***	Understand an ancient Martian hydrothermal system through study of its mineralization products and morphological expression.
Sub-Obj. 1.3	***Deep subsurface groundwater***	Understand the rocks and minerals representative of a deep subsurface groundwater environment.
Sub-Obj. 1.4	***Subaerial***	Understand water/rock/atmosphere interactions at the Martian surface and how they have changed with time.
Sub-Obj. 1.5	***Igneous terrane***	Determine the petrogenesis of Martian igneous rocks in time and space.
Objective 2	***Life***	Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.
Sub-Obj. 2.1	***Carbon chemistry***	Assess and characterize carbon, including possible organic and prebiotic chemistry.
Sub-Obj. 2.2	***Biosignatures-ancient***	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.
Sub-Obj. 2.3	***Biosignatures-modern***	Assess the possibility that any life forms detected are still alive, or were recently alive.
Objective 3	***Geochronology***	Determine the evolutionary timeline of Mars.
Objective 4	***Volatiles***	Constrain the inventory of Martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.
Objective 5	***Planetary-scale geology***	Reconstruct the history of Mars as a planet, elucidating those processes that have affected the origin and modification of the crust, mantle, and core.
Objective 6	***Environmental hazards***	Understand and quantify the potential Martian environmental hazards to future human exploration and the terrestrial biosphere.
Objective 7	***ISRU***	Evaluate the type and distribution of *in situ* resources to support potential future Mars Exploration.

select the samples to be collected by this incredibly important asset.

3. Return: The M-2020 rover has more sample tubes than are intended to be returned (see, for example, E2E-iSAG, 2011; M-2020 SDT, 2014), so it is possible that not all the samples collected will be transported to Earth. If so, some future team associated with the retrieval missions will make decisions about which samples to return. We intend this report to help provide the technical basis for those decisions. We also would like future teams to understand the relationships between samples and scientific objectives.
4. Curation and Sample Analysis: Our report is aimed at supporting planning for the curation and laboratory facilities and processes needed to make the measurements associated with achieving the objectives of MSR.

i.3 Mars Sample Return: History and Current Context

Scientific exploration of Mars has been, and continues to be, a key component of the space programs of many nations around the world (see, for example, ISECG 2018). Of the planets in our solar system, Mars is the most accessible by spacecraft, the most Earth-like in terms of geologic history and environment, and the planet in our solar system perhaps most likely to have hosted an independent origin and evolution of life. The return to Earth of geological and atmospheric samples collected from the Martian surface (and their analysis in Earth laboratories) has long been an important goal of Mars exploration.

Although planning for sample return has a very long history, the recent successes of various orbital and landed missions to Mars have in many key respects enhanced the rationale and renewed the impetus to pursue MSR.

i.3.1 Historical Perception of the Value of MSR

The potential scientific value of samples that could be returned from Mars has been seriously discussed in the scientific advisory literature for four decades, beginning with the National Research Council's *Strategy for the Exploration of the Inner Planets* (1978). Within the United States, this has then been extended through successor work by the National Research Council (NRC 1978, 1990a, 1990b, 1994, 1996, 1997, 2003, 2006, 2007a), and by the Mars Exploration Program Analysis Group (MEPAG) (McLennan et al. 2012; MEPAG 2002, 2008, 2010). Two recent, and very influential documents, are the U.S. Planetary Science Decadal Survey report (NRC 2011), which endorsed the concept of a sample-collecting rover as its highest priority in the flagship class for the decade 2013-2022, and the Mars 2020 Science Definition Team report (Mustard et al. 2013), which established the specific scientific foundation for that rover. These latter two documents formed the basis for the development of the Mars 2020 rover, which is designed to collect and cache a high-quality, "returnable" set of Martian samples. As of this writing, this mission is well along in its design and build. Within Europe, MSR has remained a fundamental and high priority (Horneck et al. 2016) and it was envisioned as a part of the European Space Agency's Aurora Programme for the 2025–2030 horizon. The ExoMars mission series is the key legacy of Aurora, and MSR is an important part of ESA's current Exploration Programme. ESA and its partners have sustained interest in studying various elements of a possible MSR campaign, including a Sample Fetch Rover (e.g., Duvet et al. 2018; Picard et al. 2018) and Earth Return Orbiter (e.g., Vijendran et al. 2018). Finally, the International Mars Exploration Working Group (IMEWG) has sponsored several analyses relating to the internationalization of MSR (Beaty et al. 2008; Haltigin et al. 2018; this report).

Although MSR in general has been consistently and strongly endorsed, the specific scientific rationale for returning Martian samples has evolved over time as our understanding of Mars has improved. The NRC (1978) report was written on the heels of the very successful *Viking* missions (launched in 1976). Following that, there was a hiatus in Mars mission activity until the missions of the Mars Surveyor Program (Mars *Global Surveyor*—1996; Mars *Pathfinder*—1996; Mars *Odyssey*—2001) and the Mars Exploration Program (Mars Exploration Rovers—2003; Mars Reconnaissance Orbiter—2005; *Phoenix*—2007; Mars Science Laboratory—2011; MAVEN—2013). During this same period, there was a 10-fold increase in the number of Mars meteorites that were available for study, including new types of sample as well as the relatively young volcanic rocks that still dominate the collection. Coupled to all of this was the rapid growth of the field of astrobiology, catalyzed by McKay et al.'s (1996) announcement of the possible discovery of evidence of ancient life in the Martian meteorite ALH 84001. As a result, the scientific value of returned Martian samples has shifted from first-order planetary-scale questions such as differentiation, to more specific questions related to understanding Martian geologic processes and conditions and determining whether Mars has, or ever did have, life.

In addition to increasing understanding of Mars and Martian processes returned samples could also assist in increasing understanding of Earth's earliest history. The oldest well-preserved (i.e., low-grade metamorphic) rocks in the Earth's crust are the 3.4 Ga rocks of the Pilbara craton in Australia and Barberton craton in South Africa, although older rocks exists (e.g., the 4.0 Ga Acasta gneiss in Canada). Because the age of the Earth is 4.56 Ga, there are more than a billion years of Earth history that are not representatively contained in its geologic record. Several significant events occurred on Earth during this period, including the probable origin of life. Mars has a beautifully preserved geologic record of a large fraction of this missing time interval. Thus, studying Mars may be our best strategy for understanding the early history of the Earth, and sample studies will play a key role.

i.3.2 The Mars Sample Return Campaign: Current Concept

The notional MSR architecture consists of three flight missions and one ground element (see Zurbuchen 2017). The three flight missions would be (1) the M-2020 sample-collecting rover; (2) a retrieval mission that would include a fetch rover and a Mars Ascent Vehicle, and have the capability to lift the samples from the surface into Martian orbit; and (3) a rendezvous mission that could transport the samples from Martian orbit to either Earth orbit or the Earth's surface. The ground element on Earth would consist of the facilities and processes needed after the samples arrive at Earth, including at least one Sample Receiving Facility and one or more sample curation facilities.

The design of the notional sample-retrieval architecture remains in the planning and discussion phase as of this writing. However, the nominal design as of 2017 was to return 31 of the M-2020 sample tubes (Edwards 2017). The intent is that there would also be an opportunity for the retrieval mission to collect 1–2 atmospheric gas samples (Edwards 2017), in containers significantly larger than the rock sample tubes. The scientific value of these gas samples is discussed as part of Objective 4 of this report. The expected size and quality of the rock and regolith samples to be collected by M-2020 are discussed in Appendix 3. Two particular notes: (1) The sampling system has been sized so that the samples are expected to be 10–15 g each for rock samples, and 8 cm^3 for regolith samples—this responds to community-sourced recommendations made by E2E-iSAG (2012) and (2) the sampling system has been designed to be responsive to a number of sample quality requirements (listed in Appendix 3). These requirements have been carefully constructed by interaction between the science and engineering communities. Although this study did not explicitly reopen and re-debate the issues of sample size and quality, we conclude that the sampling system design is responsive to long-articulated science requests.

i.4 Recent Advances that Need to Be Considered in Assessing the Expected Value of the Samples

In general terms, the samples are valuable because they would allow us to achieve certain high-priority scientific objectives. A working list of these objectives was prepared by MEPAG E2E-iSAG (McLennan et al. 2012), which did its analysis in 2010–2011 (and published its findings in early 2012). Although the E2E objective taxonomy has proved very useful in guiding MSR planning in the intervening years, there have been recent advances on several different fronts that need to be accommodated into a systematic update to these objectives.

Advances in the study of Martian meteorites. What has changed from our investigations into this set of samples? The number of Mars meteorites in our collections has now grown to over 100 (from 55 in 2011). Key new specimens include: (1) Northwest Africa (NWA) 7034: the first discovery of a Martian breccia with an ancient age and containing clasts with a range of alkaline compositions; (2) Tissint: the first observed fall of a Martian meteorite in ~50 years, which was recovered before significant terrestrial contamination could occur; (3) several basaltic meteorites with more diverse ages from the Early Amazonian period of Martian history than those already recognized, and new geochemical analyses of all the meteorites revealing multiple mantle source regions. However, as summarized by McSween and McLennan (2014) (and see the discussion under Objective 3 of this report), the population of Mars meteorites currently in our collections represents a small number of ejection events. For each such event, there is a small grouping of samples that are related to each other.

New mission results from Mars. The *Curiosity* rover landed on Mars (August 2012) after E2E-iSAG completed its work and has since operated successfully for more than 5 years. It has analyzed many solid samples (both igneous and sedimentary rocks and regolith) from an early Hesperian lacustrine environment, as well as the Martian atmosphere. The probability for MSR to find chemical biosignatures has grown stronger with *Curiosity*'s discovery of complex organic molecules; prior to the mission, it was unclear if organic compounds could be preserved in near-surface materials. The *Opportunity* rover has continued to operate far beyond its expected lifetime, for the first time exploring Noachian rocks exposed in a huge impact crater. In addition, scientific output from the wealth of data returned by orbiter missions since 2011,

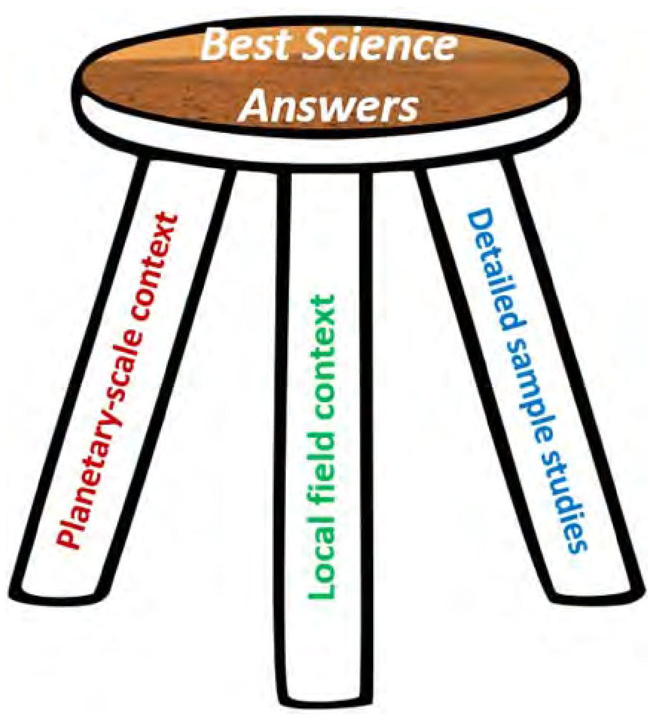

Fig. i.1. Our strategy for optimizing our scientific exploration of Mars is based on three legs. (1) Understand planetary-scale context through orbital imaging. (2) Establish local field context through the operation of instrumented rovers. 3) Conduct detailed returned sample studies. All three of these are mutually supportive—we need them all in order to fully develop our scientific understanding of Mars.

such as NASA's Mars Reconnaissance Orbiter and Mars *Odyssey*, as well as ESA's Mars Express, has been fundamentally important in shaping and improving our understanding of the Martian surface and its history.

Human exploration. We have an improved understanding of the specific ways in which returned sample studies would reduce the risk of a future human mission to Mars, and the priority of that activity (see MEPAG Goal IV, 2015a, 2015b). The most important study is to determine whether the Martian regolith and airfall dust contain biohazards that would unavoidably be ingested by the astronauts—this risk can only be evaluated by MSR.

Astrobiology. We have made significant improvements in our understandings of the potential for the preservation of the signs of life in the geologic record. A key is that we now know that the Martian environment has systematically evolved with time on a planetary scale. There were specific times, and specific places during those times, when the potential for habitability was greatly enhanced. Moreover, the study of terrestrial analog systems has given us a better understanding of the factors that affect preservation of life's signals. Together, these give us a far more effective search strategy.

Instrument developments. There have been substantial improvements in our ability to prepare and analyze very small samples in Earth laboratories. Highly visible examples are the work that has been done on the Hayabusa asteroid samples (JAXA) and Stardust comet samples (NASA). Much instrumentation development around the world continues to add to our arsenal of new techniques and approaches.

Knowledge of the expected nature of the samples. Because of the engineering development work on the M-2020 sampling system, and associated planning work on the retrieval missions, we now have a more advanced understanding of the quantity, size, and physical state of the samples which could be retrieved. These parameters must be considered in evaluating the spectrum of returned sample science that is possible.

i.5 MSR Sample Science: General Considerations

> **Finding 1:** The samples to be collected by the Mars 2020 rover can reasonably be expected to be of sufficient size and quality to address a wide variety of scientific questions if returned to Earth.

i.5.1 The Importance of Sample Context

The scientific objectives, investigations, and measurements listed below are intended to describe what can be achieved by geological and atmospheric samples returned from Mars. However, as observed by multiple prior works (e.g., MEPAG 2010; McLennan et al. 2012; Mustard et al. 2013), the value of samples is in part dependent on understanding their context. After all, a sample, by definition, is representative of something larger, and the purpose of sample study was to understand that larger entity, or process, and to answer questions that apply to more than just the sample. In order to use our detailed understanding of a sample effectively, we need to have some understanding of the geology around it. Note that context has multiple scales, from planetary, to regional, to local, and these are relevant in different ways, depending on the scale of the question being answered (Fig. i.1).

Orbital: The geological framework of all past (*Pathfinder, Spirit, Opportunity, Phoenix, Curiosity*) and future (*Insight*, M-2020, *ExoMars*) landed spacecraft was/is initially made from orbital data. Site analysis also includes a significant component of landing site safety and trafficability following landing, and morphologic and compositional data obtained from orbit are needed to meet operational requirements. Recent community landing site science assessments have been driven by morphologic and mineralogical evidence of aqueous activity. One without the other was considered insufficient justification for further consideration. To achieve the full scientific potential of samples returned from Mars, in-depth analysis of orbital data is required to provide baseline products for science analysis and operations. These products include geological maps of the site, high-resolution imaging, digital elevation models, geomorphic maps of terrain texture for rover trafficability, and compositional maps of minerals identified from visible through infrared spectral data.

Landed: Local geologic context is of paramount importance in making decisions for sample selection. While orbital data provide the context for selecting a landing site tens of km^2 in size, selection of samples requires knowledge of the exact geologic setting at the meter to submeter scale. This begins with three-dimensional surveys of outcrops to determine the stratigraphy of the geologic units followed by assessments of the mineralogy and chemistry of the geologic units. The context mineralogy and chemistry (mm to cm scale) is determined through laser, emission, Raman and infrared remote sensing techniques and fine-scale (micron to mm scale) texture, chemistry and mineralogy with imaging, APXS, X-ray fluorescence, and laser sensors. The combination of orbital context with detailed local morphology, mineralogy, and chemistry are the data needed to drive a rover to a position to use fine-scale morphology, texture, and composition sensors. At this point, the pieces are in place to make the critical sampling decisions. It is only with this nested set of quantitative data that the value of the samples can be established.

Synergy: The synergy between orbital data and in situ investigations is critically important to generate new insights that have regional and global implications. In situ investigations provide more in-depth, ground-truth analysis than orbital investigations, such as detailed mineralogy and chemistry, especially in locations covered by dust, and thus devoid of orbital signatures of minerals. It is the integration of field (planetary, regional, local) data with sample data that is scientifically so powerful. This is being managed in other parts of the general Mars exploration enterprise and is not discussed further in this report.

Synergies with the *ExoMars* mission: There are certain synergies between the Mars 2020 and the European/Russian *ExoMars* 2016/2020 missions (the 2016 *Trace Gas Orbiter* (TGO) and the 2020 lander/rover mission (Vago et al. 2017). In the first place, mapping of trace gas distribution and concentration in time and space around Mars (e.g., Webster et al. 2018) by the TGO will be an important input into choosing the timing of collecting the surface gas samples described below under Objective 4. The planetary-scale surveys of trace gas concentrations as a function of time, especially methane, will establish the context for interpreting the analytic data collected on the returned gas samples.

Perhaps more importantly, the data collected by the *ExoMars 2020* rover could play an important role in selecting and optimizing the samples to be collected by M-2020. *ExoMars* will not have the capacity to cache samples for return to Earth, so there is no scenario in which it can contribute physical samples to MSR. However, this mission will carry an extremely powerful organics detector (the MOMA instrument), and it is expected to generate key data regarding the variations in organic geochemistry in different kinds of Martian materials. *ExoMars* will have the ability to take and analyze its own samples down to a depth of 2 m, and thereby to understand the relationship of organic geochemistry and mineralogy to surface oxidative and radiolysis processes. This information, which will be generated at the same time as the M-2020 rover is carrying out its sampling operations at a different landing site, can be key to optimizing the sample selection decisions by the latter. Both *ExoMars* and the M-2020 rover will be operating in ancient geologic terrane, and by sharing their scientific understandings of the rock-forming and rock-modifying processes in early Martian geological history, they will be able to support each other. *ExoMars*' data on subsurface relationships will be valuable for helping the M-2020 team to benefit from natural geological advantages such as unconformities, differential erosion, scarps, etc.

Finding 2: Samples, by definition, are a statistical representation of a larger entity. Our ability to interpret the source geologic units and processes by studying sample subsets is highly dependent on the quality of the sample context. In the case of the M-2020 samples, the context is expected to be excellent, and at multiple scales. (A) Regional and planetary context will be established by the ongoing work of the multiagency fleet of Mars orbiters. (B) Local context will be established at field area- to outcrop- to hand sample- to hand lens scale using the instruments carried by M-2020.

i.5.2 The Importance of Sample Suites

In order to realize the full scientific potential of samples returned from Mars, it will be necessary to go far beyond that which can be learned from individual, geologically unrelated samples, which is one of the challenges faced by studying meteorites. Virtually all of the geological settings targeted by a MSR campaign to answer the most important outstanding astrobiological and geological questions are geologically complex.

Within such settings, many of the most relevant processes can only be understood by examining variability among geologically and petrologically related samples (i.e., unraveling spatial, compositional, and temporal gradients). For example, in sedimentary settings, interpretations of depositional settings and paleoclimate/climate change rely on evaluating both spatial and temporal (stratigraphic and sedimentological) relationships. In hydrothermal settings, constraining fluid pathways and alteration history (and thus identifying the most habitable niches) requires the mapping of mineralogical and geochemical gradients, often over significant distances. In volcanic settings, it is often necessary to define liquid lines of descent (associated with fractional crystallization) with multiple petrogenetically related samples to thoroughly evaluate magmatic processes and source characteristics. An individual sample taken from such complex geological settings, while no doubt extremely informative and valuable, would only sample single points in multidimensional (spatial, temporal, composition, temperature, etc.) complex systems, and thus would be inadequate for evaluating many of the most important processes.

Most of the science objectives for MSR, as they are currently envisioned, cannot be adequately addressed by a single sample or data point. Accordingly, this analysis is in agreement with other recent studies of the types and numbers of samples that should be returned by a MSR campaign that concluded that most samples should be collected and organized as well-defined “sample suites” (MEPAG 2008; McLennan et al. 2012). A “sample suite” can be defined as a set of geologically or petrologically related samples required to interpret the key biogeophysical processes that formed them. These sample suites should be strategically designed, selected, cached and returned using the best available context data and full understanding of the objectives that we hope to achieve. The optimum size of such suites is a complex issue that must balance the need for covering likely variability with the reality of limited mission resources. On Earth, it is not uncommon for such sample suites to number in the many dozens to many hundreds. For a MSR campaign, the ND-SAG (MEPAG 2008) concluded that, for the most important geological settings, sample numbers in the range of 5–8 would provide about the right balance. In practice, while such sample numbers certainly are reasonable, conditions on the ground—based on both science and resources—will dictate the final number of samples in these suites.

> **Finding 3:** A significant fraction of the value of the MSR sample collection would come from its organization into sample suites, which are small groupings of samples designed to represent key aspects of geologic or geochemical variation.

i.5.3 The Importance of Landing Site Attributes

For the M-2020 rover, NASA is currently evaluating three final candidate landing sites (colloquially known as Columbia Hills, NE Syrtis, and Jezero Crater), which have fundamentally different geology from each other. We already know that none of these sites (and no single place on Mars) covers terrane that would generate all of the samples that would be required to address all of the objectives described in this report. However, we also know that there are limits to the use of orbital data in predicting what is on the ground. A good rule of thumb is that if we can see it from orbit, it is there, but if we do not see it from orbit, it does not mean it is absent. Thus, the way to think about this report is that it is the documentation of the samples and measurements needed to achieve the scientific objectives as perfectly as possible (i.e., a wish list). What will be collected by M-2020 will almost certainly be something less than this and will depend on what is physically accessible to the rover, the nature of the discoveries it makes, how the rover’s timeline plays out, where within the landing ellipse the rover touches down, and many other factors. However, a case can be made that for the kinds of samples required or desired, it is reasonable to expect that M-2020 will be able to assemble a collection that can be used to achieve at least a part of *each* of the scientific objectives proposed. Aspects of the scientific objectives *not* covered by material collected by M-2020 or not returned to Earth in the first MSR would constitute a demand for future MSR.

Columbia Hills (175.6°E 14.5°S) is located within Gusev Crater and was previously explored by the Spirit rover during the Mars Exploration Rover mission (Squyres et al. 2004). The Columbia Hills are hypothesized to be a “kipuka” of ancient (likely Noachian or Hesperian) volcanic and/or lacustrine sediments that were embayed by the lava flows that formed the Gusev plains (e.g., McCoy et al. 2008). Within the Hills, *Spirit* discovered nearly pure silica deposits with unique digitate morphologies that have been proposed to be hydrothermal spring deposits (Ruff et al. 2011; Ruff and Farmer 2016). The Columbia Hills and surrounding basalt plains also contain a geochemically diverse suite of igneous units (McSween et al. 2006) as well as evidence for various types of aqueous alteration, including phyllosilicates (Clark et al. 2007) and an altered tephra unit containing carbonate that could be related to past lacustrine activity (Ruff et al. 2014).

Northeast (NE) Syrtis (77.1°E 17.9°N) is located in the plains on the rim of the Isidis impact basin where

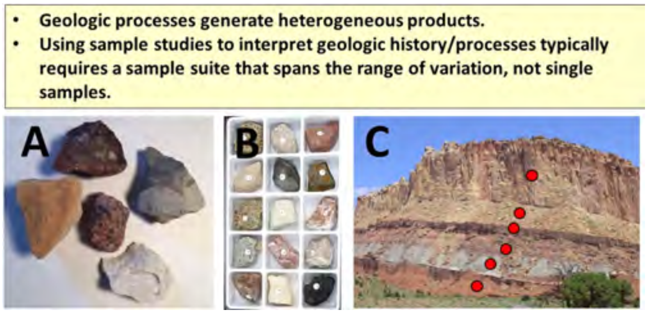

Fig. i.2. Some examples of sample suites—note that suites can be of different sizes, depending what they are intended to represent. (A) A suite of rocks showing some of the variation in the geology of Wisconsin. (B) Sample suite showing some variations in sedimentary rocks on Earth. (C) An example of stratified sedimentary rocks (on Earth), and the possible design of a scientifically useful sample suite.

erosion has exposed pre-Noachian and Noachian crustal units (Ehlmann et al. 2009). The basement unit contains primitive crust, Isidis megabreccia, large fractures, and has frequently been altered to phyllosilicates (Bramble et al. 2017). Taken together this evidence suggests the past presence of habitable deep crustal aqueous environments (e.g., Ehlmann et al. 2011a). A regionally extensive olivine- and carbonate-bearing unit mantles the basement and has been variously hypothesized to have been emplaced as impact melt, ultramafic lavas, tephra, or impact ejecta (Bramble et al. 2017; Kremer et al. 2018; Mustard et al. 2009). The carbonates may have been produced through alteration in a surface or subsurface aqueous environment (e.g., Edwards 2017; Edwards and Ehlmann 2015). The sequence is capped by a mafic unit of possible igneous origin (e.g., Bramble et al. 2017).

Jezero (77.5°E 18.4°N) is a 45 km diameter crater just north of NE Syrtis that has been interpreted as a Noachian open-basin paleolake (Goudge et al. 2012). Jezero contains several lacustrine deltas and fans (Goudge et al. 2017, 2018) fed by a large watershed interpreted to have been active in the late Noachian (Fassett and Head 2005). The crater rim is composed of the regional altered basement and is partially mantled by the same regional carbonate- and olivine-bearing unit as at NE Syrtis (Goudge et al. 2015). The stratigraphically lowest unit within the basin is the light-toned floor, which is also olivine- and carbonate-bearing (Ehlmann et al. 2008). This unit is overlain by a large delta with diverse alteration mineralogies (Goudge et al. 2017), as well as a mafic capping unit that could be consistent with either volcanic sediments or a lava flow (Goudge et al. 2015; Ruff 2017). Additional strong carbonate spectral signatures are present along the margin of the crater and may be consistent with lacustrine deposits (Horgan and Anderson 2018).

Finding 4: If the Mars 2020 rover acquires a scientifically well-chosen set of samples, with sufficient geological diversity, and if those samples were returned to Earth, then major progress can be expected on all seven of the objectives proposed in this study, regardless of the final choice of landing site. The specifics of which parts of Objective 1 could be achieved would be different at each of the final three candidate landing sites, but some combination of critically important progress could be made at any of them.

i.5.4 A Consideration: The Degree of Definitiveness of MSR

Among the various arguments discussed in this report for why returned samples would be scientifically valuable, there is a range of influence that samples from a single collection site can have. For some kinds of questions, sampling one site on Mars is sufficient, and for others, sampling one site is only the beginning. In larger context, trying to figure out the geology of an entire planet from one place conveys a certain hubris. On our own planet, by means of the hard work of thousands of geologists, we have samples that provide nearly complete coverage in time and space of the Earth's geologic record. However, the fact that some investigations are challenged with samples from only one site is not a reason not to begin the process—we cannot end up eventually with samples from multiple sites without starting with a first site. In this context, a set of samples from a single rover operations area is likely to be most useful if the geologic processes there happened over a wide range of geologic time. Individual sample-collecting rovers cannot get good planetary coverage in space, but with a well-chosen site, it is possible to obtain good coverage in time. We also have to keep in mind that there are geologic processes that move samples considerable distances on the surface of Mars, and for some of the objectives in this report, "ex situ" samples are as valuable and "in situ" ones—they can vary significantly amplify the petrologic and geochronologic diversity of the collection.

i.6 The Proposed Sample-Related Objectives for Mars Sample Return

i.6.1 Introduction

When E2E-iSAG (McLennan et al. 2012) formulated their version of the specific sample-related objectives of MSR, they presented a taxonomy of eight objectives, along with a ninth objective related to extant life that was book-kept separately (Fig. i.2). We

Scientific Objectives for MSR

From E2E-iSAG (2011)

Objective Description (in priority order)

A1	Critically assess any evidence for past life or its chemical precursors, and place detailed constraints on the past habitability and the potential for preservation of the signs of life
C1	Quantitatively constrain the age, context and processes of accretion, early differentiation and magmatic and magnetic history of Mars.
B1	Reconstruct the history of surface and near-surface processes involving water.
B2	Constrain the magnitude, nature, timing, and origin of past planet-wide climate change.
D1	Assess potential environmental hazards to future human exploration.
B3	Assess the history and significance of surface modifying processes, including, but not limited to: impact, photochemical, volcanic, and aeolian.
C2	Constrain the origin and evolution of the martian atmosphere, accounting for its elemental and isotopic composition with all inert species.
D2	Evaluate potential critical resources for future human explorers.
A2	Determine if the surface and near-surface materials contain evidence of extant life

Proposed iMOST Objectives

	Objective Description (not prioritized)	E2E Antecedent for iMOST
1	Interpret the primary geologic processes and history that formed the martian geologic record, with an emphasis on the role of water	B1, **B3**
2	Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life	**A1, A2**
3	Quantitatively determine the evolutionary timeline of Mars.	**C1**
4	Constrain the inventory of martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.	**B1, B2, C2**
5	Reconstruct the processes that have affected the origin and modification of the interior, including the crust, mantle, core and the evolution of the martian dynamo.	**C1,** C2
6	Understand and quantify the potential martian environmental hazards to future human exploration and the terrestrial biosphere.	**D1**
7	Evaluate the type and distribution of *in situ* resources to support potential future Mars exploration.	**D2**

Fig. i.3. Comparison of the scientific objectives and priorities for Mars returned sample science as organized by E2E-iSAG and by this work. The primary differences between the two schemes are that (1) for Objective 1, the critical sub-objectives of establishing geologic context, evaluating habitability or preservation potential, and assessing biosignatures assemblages have been called out; (2) the content of objectives B1 and B2 which relate to water have been repackaged into Objective 4 on the right; and (3) objectives B1, C1, and C2 have been divided

carefully considered the E2E-iSAG objectives, and after extensive iteration, we propose that E2E's structure can be rationalized into seven objectives (note that a significant fraction of the E2E committee is also a member of the iMOST committee). The first two of our proposed iMOST objectives are subdivided into sub-objectives. The refined objective structure for MSR is compared with that of E2E-iSAG in Fig. i.3, and Table i.1 shows the full set of iMOST objectives and sub-objectives.

It is important to note that even though the sample data and the field data will be integrated by scientific interpreters to achieve high-level objectives (see, for example, fig. 4 of E2E-iSAG 2012), for the purpose of this report we are considering only the incremental value that would be added by having the samples back on Earth. Commenting on measurements in the field that could be made by the M-2020 rover is outside the scope of this study.

i.6.2 How Do the iMOST Objectives Represent a Change from Previous Reports?

In summary, we have proposed a simplification of E2E's structure of nine objectives to one with only seven objectives. Primary differences between the objectives proposed by E2E-iSAG (McLennan et al. 2012) and this work, and the reasons why we have made changes, are as follows:

- We conclude that E2E's objective A1 (the past life objective) and their objective C2 (the atmosphere objective) overlap with their three B objectives (B1, B2, and B3, all of which relate to water) in a way that is overly complex. The previous three water-related objectives (B1, B2, B3) all related to habitability potential, which is an integral part of the past life objective. In addition, the extant life objective, which E2E noted but left unprioritized (due to inability to incorporate in terms of landing site or sample selection) has been retained as iMOST Objective 2.3. With regard to the atmospheric objective (C2), it does not make much sense to separate the volatile components of B1, B2, and B3. We find that all of this content this can be described more simply and effectively with two objectives, life and volatiles, which are somewhat more broadly phrased than the E2E originals.

- Missing from the E2E list is an objective related to understanding Martian geologic processes at a local scale. This relies on both field data (that will be collected by the M-2020 rover) and on sample data. We know that several of the other objectives are quite dependent on the outcome of these investigations, including the critical life and geochronology objectives. However, in addition to enabling other objectives, this knowledge is important on its own; it is therefore both a means and an end. We have inserted this as Objective 1.
- The E2E objective C1 (Quantitatively constrain the age, context and processes of accretion, early differentiation, and magmatic and magnetic history of Mars) combines two different phenomena, albeit related topics—geochronology and planetary-scale geologic processes. The samples and context needed to achieve these two objectives are quite different, so we have found it more useful to split C1 into two separate objectives (our new Objectives 3 and 5).
- The two human-related objectives (Objective 6: hazards, and Objective 7: ISRU) are carried forward essentially unchanged from the previous D1 and D2.

In addition to the above reorganization and regrouping of the objectives, we have also dropped the attempt to list them in specific priority order. Although the E2E team presented their objectives in priority order, we found that because there are some key interdependencies, sequential prioritization is difficult. For example, organic geochemistry (Sub-Objective 2.1) is one of the six classes of biosignatures listed under Sub-Objective 2.2. However, there is more to organic geochemistry than biosignatures; for example, carbon cycling is a general crustal, or even planetary, process that needs to be understood independent of biology. There is no logical way to put 2.1 and 2.2 into a sequential prioritization system, since to some extent they are each subsets of each other.

1 OBJECTIVE 1: INTERPRET THE PRIMARY GEOLOGIC PROCESSES AND HISTORY THAT FORMED THE MARTIAN GEOLOGIC RECORD, WITH AN EMPHASIS ON THE ROLE OF WATER

The geology of Mars encompasses many geological environments that have formed and been modified by a variety of processes over the course of Martian geological time. These geologic environments are not equally relevant to the high-level primary open questions associated with the current exploration of Mars (NRC 2011; MEPAG 2015a, 2015b), and there are no places on Mars where all of these environments exist together. It is therefore necessary to prioritize. For the past two decades or so, Mars exploration has been dominated by the question of whether it has ever supported life.

In this context, a key input into which Martian geologic environments are most relevant was the workshop "Biosignature Preservation and Detection in Mars Analog Environments" (documented by Hays et al. 2017). That group concluded that on Earth, signs of ancient life are best recorded in five geologic environments: sedimentary systems, hydrothermal systems, rocks that have experienced deep groundwater, environments that have experienced water/rock/atmosphere interaction, and ancient iron-rich springs. The first four of these environments are known to exist on Mars, where they are relatively widespread (see Table 1.1 and Fig. 1.1). We are not able to put them in a generic priority order, since they *all* contain evidence of life. This is not to say that we think that Mars life is exactly like Earth life or that we definitively know where to look, but that this gives us a logical strategy to start the search. As part of the landing site selection process for the M-2020 sample-caching rover, all of the sites proposed over the last several years have involved in one or more of these four ancient environments. As described above (see Section i.5.3), as of this writing the M-2020 landing site process has winnowed this down to three final candidate sites. From each it would be possible to sample rocks from at least one (and in many cases, more than one) of these four key geological environments. Clearly, a key priority for returned sample analysis is to understand the processes, timing, geochemistry, and biological potential in these four ancient geologic environments on Mars. In addition, a fifth geologic environment (Table 1.1 and Fig. 1.1) is of general interest to MSR—the igneous environment. Igneous rocks constitute probes of a planet's interior and are uniquely amenable to geochronology studies. They have played a crucial role on the Earth, the Moon, and Mars (through meteorite studies) in understanding planetary-scale geologic evolution.

Since the strategies for the optimal design of the sample suites, how those samples would be investigated, and the current state of our knowledge are quite different for the different geological environments shown in Fig. 1.1, we have chosen to designate them as five sub-objectives within Objective 1 (Table 1.1). It is our expectation that *at least* one of the first four of

Table 1.1. Division of Objective 1 into sub-objectives.

Objective 1	Geological environment(s)	Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.
Achieve **at least** one of the following sub-objectives, and as many more as possible given the local geology		
Sub-Obj. 1.1	Sedimentary system	Characterize the essential stratigraphic, sedimentologic, and facies variations of a sequence of Martian sedimentary rocks.
Sub-Obj. 1.2	Hydrothermal	Understand an ancient Martian hydrothermal system through study of its mineralization products and morphological expression.
Sub-Obj. 1.3	Deep subsurface groundwater	Understand the rocks and minerals representative of a deep subsurface groundwater environment.
Sub-Obj. 1.4	Subaerial	Understand water/rock/atmosphere interactions at the Martian surface and how they have changed with time.
Sub-Obj. 1.5	Igneous terrane	Determine the petrogenesis of Martian igneous rocks in time and space.

these sub-objectives can be achieved using M-2020 samples, in order to make progress toward our life objectives, as well as at least some progress toward the fifth (igneous) objective. (We assume for planning purposes that it will be impossible to characterize them all at any individual site on Mars.)

Establishing the detailed geologic context of a paleoenvironment specifically involves interpretation of geologic history, determining spatiotemporal relationships of different lithologies, and understanding the physicochemical conditions of rock formation/modification. The incorporation of field data obtained by the sample-collecting rover is essential.

The samples for MSR would come from one of the candidate landing sites currently being considered for the M-2020 rover (see Section i.5.3). These three candidate sites each feature at least one, and in some cases more than one, of the high-priority life-related geological environments. In advance of the completion of the M-2020 landing site selection process, it is not possible to know which of these high-priority geological

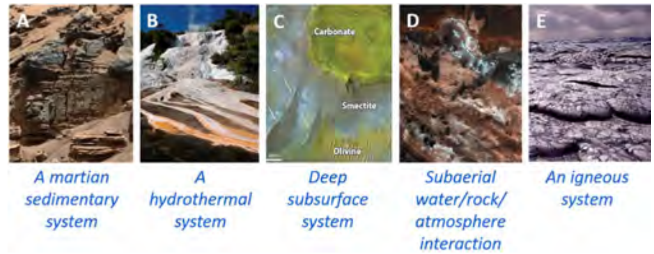

Fig. 1.1. The five geologic environments of primary interest for Objective 1. Understanding these geologic environments is both an end in itself and a means to understanding the context of the samples for other objectives. (A) (from Mars) Parallel, few centimeters thick laminations in fine-grained sedimentary rocks interpreted as lacustrine deposits at Gale Crater (Mastcam image, Hidden Valley area, *Curiosity* rover); (B) (from Earth) Hydrothermal discharge with colorful microbial communities distributed in a temperature gradient, and buildup of white siliceous sinter, Orakei Korako geothermal field, New Zealand; (C) (from Mars) Carbonated olivine-bearing rock resting on clay-rich Noachian basement crossed by mineralized fractures (white arrows) in Nili Fossae (HiRISE colored by CRISM); (D) (from Mars) Layered, phyllosilicate-rich rocks at Mawrth Vallis; bluer Al-clays overlying Fe/Mg-clays, indicating downward leaching due to surface weathering (HiRISE image); (E) (from Earth) Basaltic lava, Hawai'i.

environments will be sampleable by the M-2020 rover. The landing site selection process is designed to put these candidates in priority order, and regardless of how it comes out returned sample studies will play a critically important role.

1.1 Sub-Objective 1.1: Characterize the Essential Stratigraphic, Sedimentologic, and Facies Variations of a Sequence of Martian Sedimentary Rocks

UNDERSTAND A MARTIAN SEDIMENTARY SYSTEM	
Why is this objective critical?	*A key input into quantifying and interpreting the history of water on Mars; search for life.*
Which are the most important samples?	*One or more suites of sedimentary rocks representative of key parts of the stratigraphic section; different lithification intensity style, and timing; coarse-grained rocks with grain diversity.*

1.1.1 Introduction and Current State of Knowledge

Sedimentary systems on Earth and Mars consist of a source, sediment transport mechanisms, a depositional sink, and any postdepositional modification, thus constituting the "source-to-sink" framework (e.g., Allen 2008) in the study of sedimentary rocks (Fig. 1.2). Interpretation of the geologic record of sedimentary

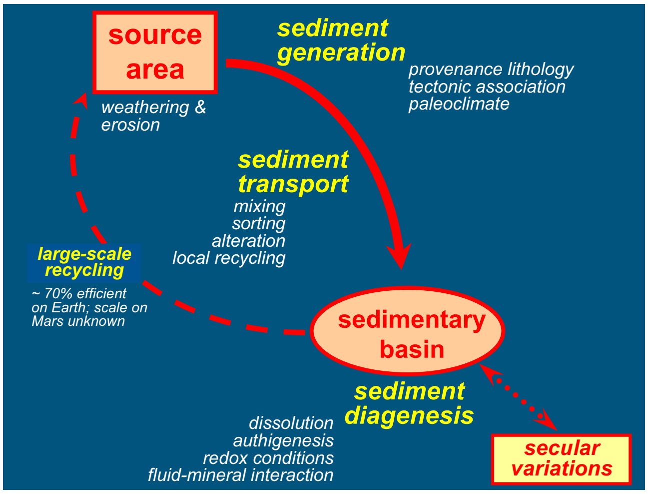

Fig. 1.2. Schematic diagram showing "source-to-sink" history of sedimentary rocks and selected examples of the types of information (white type) that can be obtained from samples. Comparisons of sedimentary rocks of differing age provide constraints on processes such as paleoclimate evolution and crustal evolution. Such approaches are known to be applicable to the Martian sedimentary record (Grotzinger et al. 2011, 2013; McLennan and Grotzinger 2008). Adapted from Johnsson (1993) and Weltje and von Eynatten (2004).

systems involves reconstruction of the paleogeometry of the sediment routing system in time and space, and the external forcing parameters (e.g., climate) that modulated the sedimentary record. The overarching goal is to quantitatively determine the evolution of planetary surface environments.

On Mars, a key goal has been to reconstruct the geometry, processes, spatial extent, and longevity of ancient aqueous environments from orbital and in situ observations with the goal of constraining habitability and guiding the search for past life. Aqueous records also provide invaluable constraints on past climate conditions and their evolution through time. Fluvial and deltaic systems provide constraints on aqueous history and guides to the search for evidence for standing bodies of water. For example, identification of ancient lacustrine environments from both orbital and in situ observations is difficult without stratigraphically correlatable deltaic and fluvial stratal evidence. Moreover, fluvial and deltaic strata provide constraints on paleohydrology, and the typically coarser grained nature (sand and conglomerates) of these strata enable analysis of grain-scale mineralogy and provenance that is difficult with finer grained strata.

Lacustrine basins (and marine basins if they ever existed) are particularly important repositories of paleoenvironmental and paleoclimatic data (e.g., Smoot and Lowenstein 1991; Renaut and Last 1994) mainly because of their potential for development of relatively continuous stratigraphic records. In lacustrine systems, variables that shape lithologies and facies are related to the surrounding environments. Climate, hydrology, tectonic, and groundwater history are all coexisting elements shaping the formation of a lithified sedimentary rock record, including the shape of the basins, geometries of sedimentary bodies and internal facies, chemical authigenic deposits, and so forth. Lacustrine sedimentary basins can provide this wealth of information whether they are hydrologically "closed" or "open." Closed basins are somewhat more sensitive to variations in external influences but even basins without- and in-flowing rivers have the potential to retain paleoenvironmental change proxies.

Paleolakes on Mars have been identified by the presence of fan deltas in more than 100 locations, predominantly in ancient impact craters and basins (Cabrol and Grin 1999; Cabrol et al. 2010; Goudge et al. 2012). Many are connected to fluvial valleys at the distal end of a regional watersheds. Crater-hosted deltas are found adjacent to Noachian highlands, and occur as deposits up to 2 km thick at Terby Crater (Ansan et al. 2011), indicating extensive aqueous activity. More recent, fresh stepped-deltas may have formed by ephemeral ponding (Kraal et al. 2008). The question of an ocean in the broader northern plains area has been debated for decades on the basis of geomorphic and topographic analysis of putative shorelines (Parker et al. 1993) and is still unresolved.

Martian lacustrine basins possess many similarities to their terrestrial counterparts and are influenced by chemical and/or physical sedimentation with high to low sedimentation rates. One important difference is that sedimentation is not matched with subsidence on Mars (e.g., Grotzinger and Milliken 2012). Sediment accommodation on Mars is interpreted to have been largely (if not totally) provided by accumulation in pre-existing basins (e.g., craters); subsidence has been absent or negligible. Absence of tectonic uplift and subsidence means that highlands are not being constantly rejuvenated and so erosion leads to decay of topography. The consequence of this is that sediment production and flux from highlands is limited compared to tectonically dominated regions on Earth. Moreover, absence of tectonic subsidence leads to sedimentary sequences likely segmented by abundant erosional surfaces (key elements in reconstructing the depositional history; Dromart et al. 2007) representing times of sediment bypass rather than deposition although mass balance requires deposition somewhere along a sediment routing system. Reconstructing the stratigraphic history of source-to-sink systems on Mars, especially within the record of terminal sinks such as lacustrine basins, is therefore a complicated puzzle.

While the climate and duration over which paleolakes formed on Mars is a matter of debate, sedimentary deposits on the floors of paleolakes provide unambiguous evidence for subaqueous deposits: these are the most appropriate locations for organic material deposition and preservation (e.g., lake basins on Earth bury more carbon per unit time than marine basins; Kelts 1988) and are therefore highest priority locations for searching for life on Mars. On Earth, biomineralized fabrics referred to as stromatolites, whose formation is influenced by microbial activity (Andersen et al. 2011; Bosak et al. 2013) and whose presence can be interpreted at the macroscopic scale (even in the absence of preserved organic carbon), form in a wide variety of environments including extreme environments. For example, modern lakes in Antarctica with frozen cover, as well as hyperalkaline and hypersaline lakes in more temperate regions, display evidence of stromatolites and deposit organic matter in extreme environmental conditions that could have occurred on Mars. Indeed, organic material preserved across the full paleoenvironmental and depositional spectrum in marine and lacustrine environments on Earth chronicles a detailed genetic history accessible through biomarker analysis (Summons and Hallmann 2014).

Table 1.2. Key open questions for Sub-Objective 1.1: Understanding Martian sedimentary systems.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.1
What was the character, composition, diversity, geological history, and age of the provenance region for the sediment that accumulated in any given depositional basin?
How was sediment generated and has that changed over geological time?
What were the dominant aqueous sediment transport processes and what were the flow conditions and discharges, sediment fluxes, and time scales of activity?
What was the history, including timing, quantity, and chemistry, of surface and near-surface water and how is the record of ancient climate of Mars preserved in the resultant sediments?
What controlled the paleogeometry of sediment transport regimes?
How did the various processes involved with sediment diagenesis operate?
What was the relationship of aqueous systems to atmospheric processes?
What is the nature of Martian aeolian processes, both in the past and at present?
Do sedimentary rocks record evidence of ancient Martian life and/or its prebiotic chemistry?

1.1.2 Key Open Questions for Sub-Objective 1.1

Figure 1.2 provides a roadmap for the major components that are involved with understanding sedimentary systems on Earth. As we gain a more sophisticated understanding of other planetary bodies with atmospheres, including Mars, it has become clear that this same source-to-sink paradigm applies to all such systems (McLennan and Grotzinger 2008; Grotzinger et al. 2013). Accordingly, the major outstanding questions that need to be addressed to decipher a Martian sedimentary system are summarized in Table 1.2, approximately in order from “source” to “sink” (which is not the same as priority order, provided below), and is largely updated from Grotzinger et al. (2011).

1.1.3 Why Returned Sample Studies Are Important to Sub-Objective 1.1

Orbiter, lander, and rover investigations have provided, and will continue to provide (e.g., with Mars2020), geological, stratigraphic, sedimentological, mineralogical, and geochemical context for source-to-sink sedimentary systems on Mars at scales ranging from $\geq 10^3$ km to ≤ 100 μm. For example, using imagery at many scales, it has been possible to build stratigraphic/sedimentological models at Gale Crater and at Meridiani Planum with remarkable fidelity and confidence. Comparable analysis will be crucial context for any sampling campaign. We also have a large database of in situ geochemical analyses at hand sample (APXS) and sub-mm (ChemCam) scales, and for selected targets we have an impressive array of mineralogical (e.g., mini-TES, Mössbauer, CheMin) and isotopic (SAM) data. Future rovers will continue to extend and enhance such measurements.

Although many of the critical scientific questions listed in Table 1.2 can be addressed by robotic investigations, in many cases they simply do not provide sufficient detail (e.g., detection limits, analytical precision, spatial resolution, etc.) to answer the questions completely. For example, micrometer-scale geochemical and isotopic data have become routine tools for modern sedimentological studies, and, while techniques such as LIBS and micro-focused XRF have remarkable capabilities, they simply do not have the spatial resolution or analytical sensitivity available in Earth-based laboratories. Figure 1.3 illustrates the range of investigations required to evaluate a clastic sedimentary rock—it is clear that such a comprehensive set of investigations, and associated analyses, could not be carried out with instrumentation at the Martian surface. Additionally, unexpected results have proven to be ambiguous without the possibility for follow-up investigations that might require different analytical capabilities. For example, the nature of the ubiquitous amorphous component found at Gale Crater (e.g.,

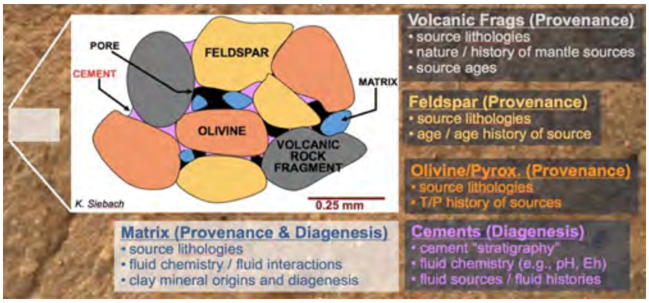

Fig. 1.3. Schematic illustration of a microscopic view of a clastic sedimentary rock, illustrating types of information that can be obtained through study of various components (different grains, matrix material, different generations of cements) at a microscopic (submicron to millimeter) scale (adapted from http://slideplayer.com/slide/8858365/). Many of the analytical methods required to obtain the required mineralogical, textural, structural chemical, and isotopic data, such as in situ high-resolution microbeam techniques (e.g., ion microprobes, LA-MS) and other cutting-edge laboratory instruments (e.g., TIMS, GC-MS, AMS, STEM, FIB-SEM), must be carried out in Earth-based laboratories.

Morrison et al. 2018) cannot be fully resolved with available rover measurements at Mars but could be readily characterized by modern synchrotrons (e.g., Michel et al. 2007; Manceau et al. 2014), which include many beamline techniques that in general have widespread application to small sedimentary samples (e.g., Manceau et al. 2002). The ultimate resolution of many of the critical questions listed above may rely on cutting-edge analytical methods and associated sample preparation (e.g., Raman microscopes, electron microscopes, FIB microscopes, ion microprobes, synchrotrons, laser ablation mass spectrometers, accelerator mass spectrometers) that either cannot be taken to Mars, or would not operate effectively there. Finally, the repeatability of critical measurements is readily achievable by interlaboratory comparisons on Earth, but is impractical on Mars.

1.1.4 Sample Investigation Strategies to Achieve Sub-Objective 1.1

The scale of sedimentary systems on Mars can be of the order of thousands of km across (e.g., Grotzinger and Milliken 2012), whereas the scale of rover operations is expected to be at most tens of km. It is not possible with current rover technology to visit and sample all the aspects of a sedimentary system that may be required to understand source-to-sink processes. Nevertheless, the sedimentary facies analysis methods for reconstructing sedimentary processes and environments provides powerful tools to reconstruct sedimentary systems and provide guidelines for reasonably representative sampling of a sedimentary basin at rover scales, as demonstrated at Gale Crater (Grotzinger et al. 2015) and Meridiani Planum (Grotzinger et al. 2005).

At a well-chosen site in a Martian sedimentary system, it should be possible to obtain appropriate samples to carry out many, if not most, of the proposed investigations required to meet the scientific objectives associated with returned sedimentary samples. Sedimentary systems offer a distinct tactical advantage during rover operations; experiences at Meridiani Planum and Gale Crater have shown that in situ data collection permits high-fidelity refinement of working facies models which, in turn, provide a framework to guide hypothesis testing and the prioritization of subsequent analytical (including sampling) targets. Because of their frequent association with water and aqueous processes and their well-preserved nature on Mars, sedimentary systems also provide the highest chance for finding potential traces of life. The proposed Investigation Strategy requires the characterization of a sedimentary system at a range of scales of observation, from macroscopic to microscopic, with samples from key stratigraphic units that best address the largest number of high-priority questions.

We propose six specific investigation strategies and 21 sets of measurements on samples returned from a Martian sedimentary system (Table 1.3). The investigation strategies are listed in approximate priority order.

***Investigation Strategy 1.1A*: Investigate physical and chemical sedimentary processes in standing or ponded water to understand more completely the occurrence of sustained, widespread liquid surface water on Mars, including the examination of evaporites resulting from such processes.**

Although orbital observations can constrain the nature of depositional basins and their sedimentary mineralogy, the reconstruction of the geological history of these basins cannot be performed satisfactorily without the analysis of returned samples. This is even more compelling in the presence of chemical deposits, such as evaporites, siliceous sediments, or carbonates that may originate by precipitation directly from the water column, and therefore record chemical and other paleoenvironmental aspects of their parent waters through time.

Sedimentary deposition in standing water may chronicle the interface between surface water and groundwater on Mars (e.g., Hurowitz et al. 2010). This, in turn, permits a broader understanding of regional hydrological influences on sedimentation, and thus the spatial and temporal extent of sedimentary episodes driven by liquid water on Mars (Fig. 1.4). For example, data collected by the Mars Exploration Rover

Table 1.3. Summary of sample-related investigation strategies to understand a Martian sedimentary system.

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.1		
1	**Geological environment(s)**	**Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.**
1.1	Sedimentary system	Characterize the essential stratigraphic, sedimentologic, and facies variations of a sequence of Martian sedimentary rocks.
IS 1.1A	Investigate physical and chemical sedimentary processes in ponded water to understand more completely the nature and distribution of sustained, widespread liquid surface water on Mars, including evaporite minerals and fluid inclusions.	
IS 1.1B	Investigate sediment diagenesis, including the processes of cementation, dissolution, authigenesis, recrystallization, oxidation/reduction, and fluid–mineral interaction.	
IS 1.1C	Investigate the mechanisms by which sediment is/was generated on Mars, by understanding the weathering and erosional processes.	
IS 1.1D	Investigate the provenance of the sediment in the sedimentary system to determine source area geology, mineralogy, as well as weathering processes and products.	
IS 1.1E	Investigate the nature of subaqueous (and subglacial) sediment transport processes responsible for erosion of valley and channel networks, and deposition of fluvial, deltaic, and lacustrine facies. Determine flow discharges and sediment flux, intermittency of deposition, time scales of deposition, and paleoclimate conditions.	
IS 1.1F	Characterize the physical properties of aeolian materials to understand aspects of surface processes and climate history.	

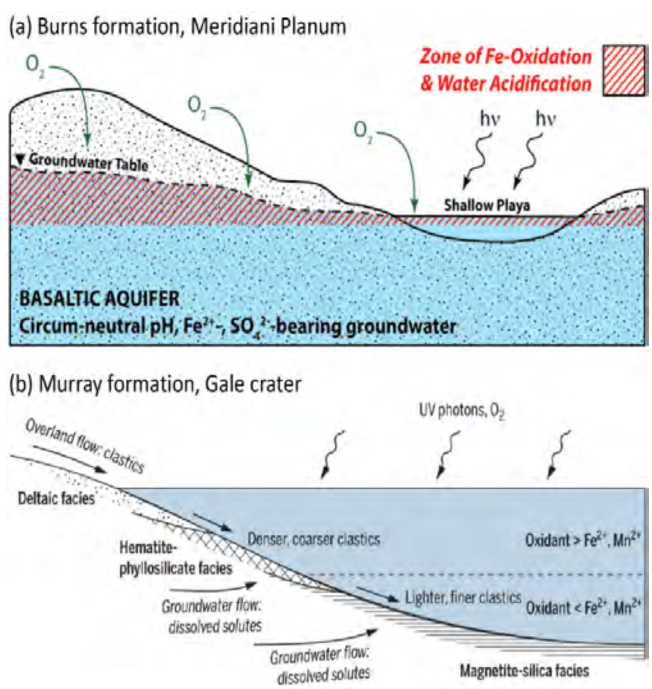

Fig. 1.4. (a) Groundwater–atmosphere interaction in the Burns formation, Meridiani Planum (Hurowitz et al. 2010). Reduced groundwaters from a basaltic aquifer become oxidized when in contact with the atmosphere near the top of the groundwater table or in ephemeral playa lakes, resulting in low pH aqueous conditions, evidence for which is preserved in diagenetic phases in Burns formation sediments. (b) Redox stratified lake model for mudstones of the Murray formation, Gale Crater (Hurowitz et al. 2017). An ancient redox stratified lake in Gale Crater is fed by surface flow and groundwater. Evidence for alternating redox conditions is preserved within the sediment mineralogy which changes from a relatively oxidized hematite–phyllosilicate (HP) shallow water facies to a relatively reduced magnetite–silica (MS) deeper water facies.

Opportunity support a strong regional hydrological control on sedimentation and diagenesis (e.g., Grotzinger et al. 2005; McLennan et al. 2005; Hurowitz et al. 2010), and the importance of this influence was reinforced at Gale Crater by *Curiosity* (Grotzinger et al. 2005; Hurowitz et al. 2017). These data contributed to a new understanding of the nature and extent of groundwater systems on Mars and their response to global climate change (e.g., Andrews-Hanna et al. 2007). Lake basins receiving a significant groundwater influx on Mars (including Gale Crater; Horvath and Andrews-Hanna 2017) have been recognized on the basis of volume to drainage area ratios (Fassett and Head 2008), which increases the likelihood that a well-chosen lacustrine sedimentary site may record large-scale hydrological events expressed across multiple sedimentary basins.

Moreover, visual observations from a rover can identify discontinuities such as unconformities and erosional surfaces because they are the most compelling expressions of erosional processes. Specifically in the case of lake deposits, identification of sedimentary bodies, such as deltaic sediments (foresets or bottomsets), or of deepwater river deposits, will enable the characterization of direct contributions from fluvial activity. Sample analysis when coupled with an integrated reconstruction of stratigraphic sequences and identification of subregional unconformities has the potential to enable assembly and interpretation of the geologic history of Mars.

Table 1.4 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.1A and move toward understanding of a Martian sedimentary system.

Table 1.4. Samples and measurements implied by Investigation Strategy 1.1A.

Samples identified to advance Investigation Strategy 1.1A:

- A suite of sedimentary rocks representative of the stratigraphic section

Measurements identified to advance Investigation Strategy 1.1A:

- Provide geologic context by measuring stratigraphy and determining structure of samples from the stratigraphic section.
- Capture microscale sedimentary structures (laminations thickness, small ripples, etc.).
- Measure mineralogy and chemistry of both clastic and chemical sediments (including fluid inclusions) in a stratigraphic framework.
- Perform provenance and geochronology studies of sediments.
- Measure textural parameters of sediments including grain size, grain shape, sorting of sediments.
- Evaluate subsidence and accommodation space as part of understanding basin-scale processes.

***Investigation Strategy 1.1B:* Investigate sediment diagenesis, including the processes of cementation, dissolution, authigenesis, recrystallization, oxidation/reduction, and fluid–mineral interaction.**

Diagenetic processes include all changes in texture, chemistry, and mineralogy by fluid circulation, heat, and pressure leading to the cementation of initially loose sediments, as well as any relatively low-temperature post-lithification changes (e.g., veins, concretions, secondary porosity, and pressure solution). These processes are fundamental in our understanding of the initial depositional environments, because early diagenetic processes (i.e., those occurring while diffusional contact with the overlying water column is maintained; or before lithification) reflect those that may be confined to sedimentary pore waters, but may influence the chemical budget of the overlying water column (e.g., microbial metabolic influences in marine or lacustrine sediments on Earth, or redox stratification at Gale Crater; Hurowitz et al. 2017). For example, experimental work suggests that syndepositional or early diagenetic magnetite formation in Gale Crater mudstones may have been driven by groundwater infiltration into lacustrine sediments which also generated H_2(g) (Tosca et al. in press). This implies that early diagenetic processes may have strongly impacted surface and perhaps atmospheric chemistry on early Mars, while at the same time offering uniquely favorable environments for metabolic processes known to be ancient on the Earth (i.e., methanogenesis via the acetyl-CoA pathway, which depends on the presence of H_2 and CO_2; Braakman and Smith 2012).

Diagenetic processes also modify initial sedimentary compositions. For instance, many outcrops where clay minerals have been detected by orbital spectrometers are part of sedimentary deposits, but it is often impossible to determine unambiguously if the minerals were formed in situ (authigenic) or were transported from previously weathered ancient crust (allogenic). While this difference is fundamental to understanding the conditions under which clay minerals formed, the mineral phases, taken independently, are rarely sufficient to discriminate between the two origins (e.g., Milliken and Bish 2010). On Earth, microscopic observations of the texture of rocks are used to discriminate between these scenarios by distinguishing clastic grains from cements and authigenic phases.

Diagenetic processes are also important in understanding postdepositional environments and aqueous episodes occurring after sediment burial. At rover scales, veins and concretions observed by both *Opportunity* and *Curiosity* have led to fundamental insights into postdepositional environments. The association of authigenic minerals (jarosite) and hematite-rich concretions point toward acidic fluids at Meridiani Planum (e.g., Squyres and Knoll 2005) (Fig. 1.5); the conditions may be relatively localized and related to groundwater redox processes (Hurowitz et al. 2010) (Fig. 1.4a). At Gale Crater, *Curiosity* identified a variety of phases, such as calcium sulfate veins, Mg-rich concretions, and halos of opaline silica (Figs. 1.5b and 1.5c) that imply several episodes of fluid circulation that were not recognized from orbital data (e.g., Frydenvang et al. 2017; Nachon et al. 2017). However, rover observations are greatly limited by the size of features and the types of analyses possible. Microscopic observations (down to the submicron scale) would enable the determination of relative chronologies of different episodes of diagenesis by the identification of paragenetic sequences of diagenetic features. Stable isotopes on authigenic minerals would help determine conditions (e.g., temperatures, depth) of formation (e.g., Anderson et al. 1976; Swart 2015). Precise radiometric isotope dating of cementing agents or K-rich authigenic components (such as goethite and hematite, and jarosite, respectively) would be best accomplished in terrestrial laboratories.

Diagenetic processes would modify the preservation of organic material potentially present in aqueous sediments, either by degrading the textures of microfossils, or replacing their initial composition by authigenic minerals in response to fluid episodes (e.g., Hernández-Sánchez et al. 2014). At the same time, some diagenetic processes may liberate chemicals that promote chemosynthetic pathways for C-fixation, which may in turn promote organic matter production. In either case, laboratory-based microscopic observations would enable a detailed assessment of the rock to determine whether the mineral phases are relevant to

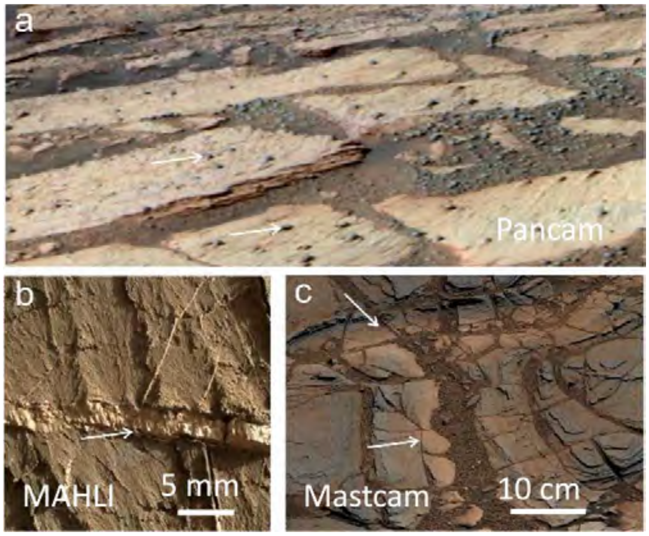

Fig. 1.5. Images illustrating diagenetic features observed in sedimentary rocks on Mars that show the action of aqueous fluids and variable physicochemical conditions (e.g., pH, Eh, temperature) linked to surface and/or subsurface environments. Diagenetic overprints may influence preservation of biological material or prebiotic chemistry. (a) *Opportunity* Pancam observations of sedimentary rocks in the Burns formation at Meridiani Planum showing 5 mm diameter iron-rich (hematite) concretions (arrows) resulting from fluid circulation during diagenesis. (b) A 5 mm thick light-toned vein (arrow) observed at Gale Crater by the MAHLI imager onboard the *Curiosity* rover. It is composed of sulfate minerals such as gypsum and bassanite resulting from precipitation of sulfur-rich fluids inside fractures formed by hydraulic fracturing after rock cementation. (c) Light-toned halo (arrows) observed by *Curiosity* at Gale Crater formed around a fracture zone (partly filled by sand). The halo is made of silica predominantly (including opaline silica) and is a result of late-stage diagenesis.

diagenetic episodes or formed prior to burial of the sediments. Thus, diagenetic processes are fundamental for making an in-depth assessment of the exobiological potential of a sedimentary rock. Acquiring such samples at various degrees of cementation would enable characterization of the diagenetic processes at various stages and disentangle these episodes from initial depositional processes.

Table 1.5 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.1B and move toward understanding of a Martian sedimentary system.

Table 1.5. Samples and measurements implied by Investigation Strategy 1.1B.

Samples identified to advance Investigation Strategy 1.1B:

- A suite of sedimentary rocks showing a range of lithification intensity and style.

Measurements identified to advance Investigation Strategy 1.1B:

- Determine the mineralogy of sedimentary rocks and evaluate the possibility of secondary minerals that may have formed as cement in the pore network.
- Determine the paragenetic sequence, including both overgrowth relationships and mineral dissolution events.
- Measure the radiometric ages of the cement with permissible mineralogy (e.g., jarosite by K-Ar, calcite by U-Pb, etc.)
- Determine how diagenetic processes may either enhance or obscure possible taphonomy.

***Investigation Strategy 1.1C:* Investigate the mechanisms by which sediment is/was generated on Mars, by understanding the weathering and erosional processes (the interrogation of chemical weathering is also discussed further under Investigation Strategy 1.4A).**

The initial process in the "source-to-sink" history of a sedimentary basin (Fig. 1.2) is weathering, involving both the physical breakdown and chemical alteration of source rocks, processes occurring simultaneously and in a synergistic manner (Johnsson 1993). Orbital remote sensing, in situ measurements of mineralogy and geochemistry, and laboratory experiments (see reviews in McLennan and Grotzinger 2008; McLennan 2012; Grotzinger et al. 2013) provide a growing body of evidence that a variety of chemical weathering processes have operated on Mars and that the records of such processes, to the degree that in situ rover measurements permit, are observable in Martian sedimentary rocks (e.g., McLennan et al. 2014; Mangold et al. 2017). Chemical weathering involves alteration (i.e., element fractionation resulting from mineral dissolution), precipitation of secondary mineral phases, separation and redistribution of primary and secondary minerals, rock fragments, elements, and stable and radiogenic isotopes (e.g., McLennan et al. 1993, 2003; Nesbitt 2003). In detail, such processes may be complex and occur within soil profiles developed in source terrains, during transport of sediment from source to sink, and during short-term episodes of deposition/re-erosion as sediment is transported through the sedimentary system from initial source to final depositional basin. The mineralogical, chemical, and isotopic compositions of sedimentary rocks are influenced by chemical weathering and are deposited at any given time, therefore providing a proxy for the penecontemporaneous climate integrated over the catchment region (e.g., West et al. 2005; Gislason et al. 2009). Accordingly, many stratigraphic profiles provide faithful records of climate change.

Table 1.6 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy

Table 1.6. Samples and measurements implied by Investigation Strategy 1.1C.

Samples identified to advance Investigation Strategy 1.1C:
- Rocks that show a range of weathering styles and weathering intensity, including weathering rinds, if present.
- Sedimentary rocks with a variety of grain compositions (heterolithic).
- Modern regolith, especially if locally derived.

Measurements identified to advance Investigation Strategy 1.1C:
- Determine the minerals formed by weathering processes over a range of distinct parent lithologies.
- Determine the mineralogy and mineral chemistry of the sedimentary grains, and their relationship with the parent lithologies.
- Determine the proportion of grains derived from igneous, metamorphic, and sedimentary rocks (and associated geochronology measurements, since there are many weathering minerals that can now be dated, such as hematite, goethite, etc.)

1.1C and move toward understanding of a Martian sedimentary system.

***Investigation Strategy 1.1D*: Investigate the provenance of the sediment in the sedimentary system, including variation in lithology, tectonic association, and paleoclimate.**

A fundamental control on the mineralogical, chemical, and isotopic composition of sedimentary rocks is the original composition of igneous–metamorphic–sedimentary source rocks in the catchment regions of the source-to-sink system—the sediment provenance. A primary goal of sedimentary petrology is thus to constrain the provenance (e.g., Garzanti 2016) and in turn interpret that provenance in terms of the geology (i.e., lithologies) of the source regions, relationships to tectonic associations, role of sedimentary recycling, relationships to paleoclimate, and implications for the ultimate magmatic history (i.e., crust–mantle evolution) of the igneous sources (see reviews in McLennan et al. 1993, 2003; Veizer and Mackenzie 2014). The study of sedimentary provenance has become increasingly sophisticated and bulk rock petrographic, geochemical, and isotopic approaches (e.g., Dickinson 1970; McCulloch and Wasserburg 1978; Bhatia 1983) have given way to studies where provenance may be evaluated quantitatively, often on a "grain by grain" basis (e.g., Vermeesch 2004; Fig. 1.3). This approach applies a myriad of geochemical and isotopic methods to a variety of individual (typically sand-sized or larger) grain types, including, for example, U-Pb dating of individual zircon (often combined with O-isotope and Lu-Hf isotope characterization of the same grains), monazite, rutile, and quartz grains; Pb isotope compositions of individual quartz, feldspar, and hornblende grains; $^{40}Ar/^{39}Ar$ ages of a variety of detrital minerals; and so forth (see review in McLennan et al. 2003). Such approaches will be especially important for samples returned from Mars where bulk sample numbers will be limited, but where individual sand-sized grains within sediments and sedimentary rocks may effectively be treated as separate samples that can be evaluated petrographically, geochemically, and isotopically. As described in Fig. 1.3, the types of grains/minerals that can be evaluated on "basaltic" Mars will differ fundamentally from most terrestrial experience.

Table 1.7 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.1D and move toward understanding of a Martian sedimentary system.

***Investigation Strategy 1.1E*: Investigate the nature of subaqueous (or subglacial) transport regimes that cut channels and valleys, including whether they were persistent or episodic, the size of discharge, and the climatic conditions and time scales of formation.**

The exobiological potential of a sedimentary landing site depends on several variable including the presence of water, the burial processes, the amount of biota and their activities, etc. High discharge rate channels, such as those found in catastrophic floods, involve highly turbulent flows moving large blocks, thus disfavoring a good preservation of organics. Lakebeds, variations of fluvial regimes, river systems such as meandering or braided channels, the presence of floodplain deposits can be processes and deposits that favor biological activity and the preservation of its signature. The

Table 1.7. Samples and measurements implied by Investigation Strategy 1.1D.

Samples identified to advance Investigation Strategy 1.1D:
- Relatively coarse-grained clastic sedimentary rocks. Most valuable would be rocks containing at least some multi-mineralic sedimentary grains (i.e., small rocks), which could be studied independently.

Measurements identified to advance Investigation Strategy 1.1D:
- Determine the mineralogy and mineral chemistry of lithic fragments and mono-mineralic grains.
- Determine the crystallization ages of lithic clasts and appropriate minerals, where possible (e.g., within coarse clasts) using radiometric dating.
- Determine an integrated surface exposure age of the source regions by measuring cosmogenic nuclides.

floodplain environment is the best candidate to harbor biological signatures. These environments are linked to Earth-like fluvial activity where the presence of fluvial channels is matched by crevasse splays or overbank deposition. Curiosity rover has analyzed locally fluvial conglomerates and sandstones providing first-order analyses of fluvial sedimentary facies, flow rates, and clast composition (Williams et al. 2013; Mangold et al. 2016; Edgar et al. 2018). Microscopic analyses of a series of sedimentary rocks from cross-bedded sandstones to mudstones would enable scientists to determine the sorting effects related to depositional processes such as unidirectional currents versus wave action and the degree of roundness of grains in order to provide information on distance and time of grain transportation (e.g., Whalley 1978; McLaren and Bowles 1985; Le Roux and Rojas 2007). Facies analysis at microscopic scale can also provide information on the type of conditions during deposition, such as those due to desiccation or frost. For instance, sedimentary deposits in subglacial lakes in Antarctica show specific microstructures that are specific to this surface environment (Andersen et al. 1993; Hendy 2000; Rivera-Hernandez 2018).

Table 1.8 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.1E and move toward understanding of a Martian sedimentary system.

***Investigation Strategy 1.1F:* Characterize the physical properties of aeolian materials to understand aspects of the surface processes and climate history**

Orbital observations and surface missions demonstrate that aeolian processes have played a dominant role in the development of the Martian planetary geomorphic surface and stratigraphic record. Even within a largely fluvio-lacustrine basin, evidence for aeolian processes is likely to be encountered. Evidence for aeolian reworking occurs within the fluvial Shaler outcrops, as documented by the *Curiosity* rover within Gale Crater (Edgar et al. 2018). Within a lacustrine stratigraphic record, the significance of wind-scoured surfaces and aeolian deposits is that these represent hiatuses in subaqueous deposition, and basin-scale examples are paleoenvironmental signals. Within Gale Crater, a likely wind-scoured unconformity with tens of meters of relief (Watkins et al. 2016) scours into the lacustrine Murray formation (Grotzinger et al. 2015) and is overlain by the aeolian Stimson formation, thus signaling a major environmental change (Banham et al. 2017); that, however, did not preclude the presence of biological signatures in the dune deposits (Fisk et al. 2013). Aeolian samples may also advance our understanding of the Martian volatile budget. In the Bagnold Dune Field sands (at Gale Crater), H, S, and Cl were depleted (probably because of Martian dust being physically removed) but C- and N-bearing phases are elevated. Whether this is related to organic matter from meteorites, modern products of interaction with the atmosphere, or some other cause is not clear with currently available data (Bridges and Ehlmann 2018).

Within a predominately lacustrine stratigraphic record, aeolian processes are likely to be manifested as (1) erosional (deflationary) surfaces, (2) aeolian dry system accumulations, and (3) aeolian wet system accumulations. Even without overlying aeolian deposits, wind-scoured surfaces indicate a hiatus in subaqueous deposition of varying temporal and spatial extent. Where dry system dune strata occur overlying these surfaces, their preservation on Mars requires surface flooding or a rise in the water table. Wet aeolian systems occur where the water table is near the surface, and these are both most likely to occur associated with lacustrine strata and are the most intriguing for a biological signature. On Earth, aeolian wet system deposits typically represent an assemblage of sabkha, sand sheets, adhesion structures, and microbial mats. Examples of microbial mats within aeolian deposits have been identified in the rock record of early Earth (Simpson et al. 2013). The middle and upper units of the Burns formation, as studied by the *Opportunity* rover in Endurance Crater are interpreted as wet aeolian deposits (Grotzinger et al. 2005).

The advantages of a returned sample over orbital or rover data are many. Aeolian sediments may be derived from the reworking of local deposits or from

Table 1.8. Samples and measurements implied by Investigation Strategy 1.1E.

Samples identified to advance Investigation Strategy 1.1E:

- A suite of sedimentary rocks representative of stratigraphy associated to ancient stream channels.

Measurements identified to advance Investigation Strategy 1.1E:

- Measure mineralogy and chemistry of both clastic and chemical sediments, capturing different stratigraphic positions.
- Perform provenance and geochronology studies of sediments.
- Measure texture, grain size, and grain shape of sediments.
- Measure mineralogy and chemistry of both clastic and chemical sediments, capturing different stratigraphic positions.

multiple sources external to the basin, thus mixed provenance signals may be present. Grain mineralogy may be obscured by dust coatings. Orbital data (e.g., CRISM) is too coarse in resolution to make these fine distinctions, and in situ sampling (e.g., LIBS) has a limited compositional range and entire grain populations are not treated. Grain size range cannot be fully resolved from rover images, and it is unclear if dust is transported as individual grains or as aggregates. Both issues are readily addressed in a laboratory via laser or image particle analyzers. Wet aeolian system deposits especially are likely to contain fine grains transported as suspended dust, whereas ripple and dune strata represent the traction (creep and saltation) load. Given an analysis of the full spectrum of grain sizes, the wind energy needed for transport can be derived. Finally, the diagenetic history of aeolian strata may be different from that of associated subaqueous deposits, and grain surface weathering products cannot be measured with current in situ bulk analyses. Both aspects are readily addressed in the laboratory. Modern aeolian sediment and lithified aeolian sedimentary rock in the same area may be widely separated in time, thus representing different environmental conditions, provenance and grain histories. Moreover, the texture (i.e., grain packing, alignment, porosity) of the aeolian deposits and diagenetic history will only be evident in a sedimentary rock. Samples should be collected both from modern aeolian sand on the surface, and from individual stratigraphic horizons where aeolian rock outcrops.

Table 1.9 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.1F and move toward understanding of a Martian sedimentary system.

Table 1.9. Samples and measurements implied by Investigation Strategy 1.1F.

Samples identified to advance Investigation Strategy 1.1F:
- Sample of modern aeolian sediment from the surface.
- Sample(s) of lithified aeolian sedimentary rock (at different stratigraphic horizons).

Measurements identified to advance Investigation Strategy 1.1F:
- Determine the mineralogy of sand and dust fractions in order to identify source areas.
- Determine the grain size range, sediment sorting, and sand grain shape in order to reconstruct the wind transport.

1.2 Sub-Objective 1.2: Understand an Ancient Martian Hydrothermal System Through Study of its Mineralization Products and Morphological Expression

UNDERSTAND A MARTIAN HYDROTHERMAL SYSTEM	
Why is this objective critical?	*A key input into interpreting the history of water on Mars; search for life.*
Which are the most important samples?	*One or more suites of hydrothermal samples and/or altered host rocks representing variations in position, time, chemistry, and/or mineralogy (e.g., proximal to distal) relative to the hydrothermal vent*

1.2.1 Introduction and Current State of Knowledge

Highly promising locales for exploring the ancient environment of Mars, including prospecting for preserved biosignatures, are places where heat from volcanism or impacts interacted with surface water, including ice, to form hydrothermal systems. Hydrothermal processes are fundamental phenomena that occurred and continue to occur as part of the fabric of the solar system's evolution, from colliding bodies to water (or ice)–rock interactions within growing planetesimals and nascent planets that have built up their mineral inventories over time (Hazen et al. 2008). Hydrothermal systems (Fig. 1.6) link global atmospheric, hydrologic and lithospheric cycles, as well as connect surface and shallow subsurface realms via fluid flow, on Earth and likely Mars. Furthermore, all large impact structures on Earth are associated with evidence for hydrothermal activity. These were

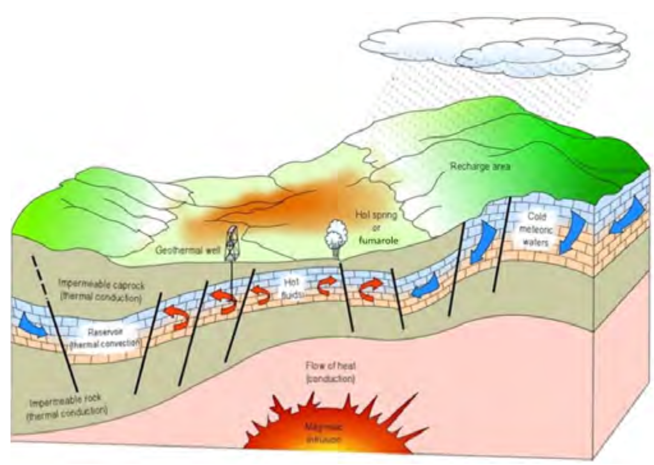

Fig. 1.6. Hydrothermal circulation interacting with the lithosphere, atmosphere, hydrosphere and biosphere (Dickson and Fanelli 2004).

important hydrothermal systems—especially on early Earth (Lowe and Byerly 1986)—and one of the few terrestrial hydrothermal systems with a direct analog on Mars. Hydrothermal minerals (e.g., jarosite, alunite) are useful for dating hydrothermal activity, and for extracting paleoclimate information and alteration history in these settings (Stoffregen et al. 2000). They are known on Earth throughout the geological record (~3.5 Ga to present), and they not only host life—including "extreme" life adapted to conditions that may be present elsewhere in the solar system—but they also preserve robust mineralogical, textural, and compositional evidence of ancient microbial biosignatures (e.g., Farmer 2000; Konhauser et al. 2003; Trewin et al. 2003; Handley et al. 2008; Westall et al. 2015a; Djokic et al. 2017), and may have been the setting for the origin of life on Earth (e.g., Mulkidjanian et al. 2012). Evidence for ancient hydrothermal systems on Mars has been presented from several sites (e.g., Newsom 1980; Gulick 1998; Schulze-Makuch et al. 2007; Allen and Oehler 2008; Rossi et al. 2008; Ehlmann et al. 2009, 2011b; Marzo et al. 2010; Skok et al. 2010; Mangold et al. 2012; Thollot et al. 2012; Osinski et al. 2013; Carrozzo et al. 2017; Michalski et al. 2017; Thomas et al. 2017). These include Gale Crater (Zn- and Ge-enrichment measured by Curiosity rover; Berger et al. 2017), and two of the three finalist M-2020 candidate landing sites: Columbia Hills (Squyres et al. 2008; Ruff et al. 2011; Ruff and Farmer 2016), and NE Syrtis Major (Mustard et al. 2007, 2008; Ehlmann and Mustard 2012; Bramble et al. [2017] and references therein). Some inferred Martian hydrothermal phenomena have involved magmatic interactions with glaciers or valley networks (e.g., Abramov and Mojzsis 2009; Ackiss et al. 2016; Bouley et al. 2016). Both early and late diagenetic hydrothermal signatures have been identified (e.g., Yen et al. 2008; Ruff et al. 2011; Berger et al. 2017).

Here we discuss hydrothermalism as related to groundwaters reaching the surface, whereas Section 1.3 (Sub-Objective 1.3) deals with accessing the hydrothermal groundwaters.

1.2.2 Key Open Questions for Sub-Objective 1.2

Hydrothermal deposits represent a category of an ancient geologic environment long recognized as an important target for astrobiological exploration of Mars (Walter and Des Marais 1993; Farmer and Des Marais 1999; Michalski et al. 2017), and now found to be at least locally present in the Martian geologic record (Fig. 1.7), for example, at Columbia Hills (Squyres et al. 2008; Ruff et al. 2011; Ruff and Farmer 2016). On Earth, hydrothermal environments are inhabited by extremophiles with deep phylogenetic roots in the three-domain "tree of life" (Woese and Fox 1977; Reysenbach et al. 2001). Critically, all the known hot-spring deposits on Earth, extending from the present day back to at least 3.5 billion years of the geological record, contain a variety of preserved biosignatures (e.g., Walter et al. 1996; Guido and Campbell 2011; Djokic et al. 2017), even at the high temperatures recorded around vents (e.g., ~100 ^{0}C of continental hot springs; Campbell et al. 2015a).

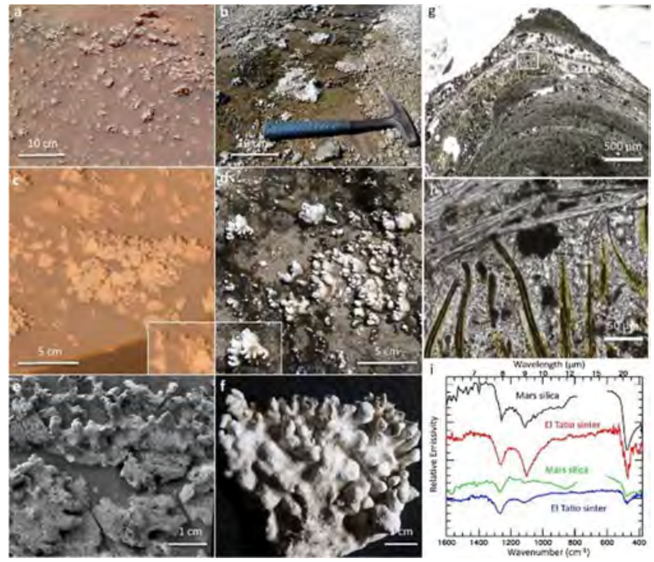

Fig. 1.7. Scale-integrated comparison of opaline silica in the Columbia Hills of Gusev Crater, Mars versus modern hot-spring silica deposits (sinter) produced in outflow channels of El Tatio, Chile. The nodular and digitate expression and distribution of Martian silica (a, c, e) is comparable to that of the Chilean silica (b, d, f). Thin-section analysis of Chilean silica (g, h) shows filamentous microbes entombed during formation of digitate structures (microstromatolites). Thermal infrared spectra (i) reveal similarities at the molecular scale between Martian and Chilean silica, with spectral variations attributable to the variability of a halite (NaCl) crust; more halite in green and blue spectra, less in black and red spectra. Modified from Ruff and Farmer (2016).

Sources of hot water on early Mars would have melted ice, at least locally, by geothermal heat flow, igneous processes (e.g., subsurface magmatic and volcanic), and/or meteorite impacts. The climatic and bombardment history of Mars may have allowed only a short window for evolution and/or punctuated surface habitability (Westall et al. 2015a). If so, then life that may have developed probably would have been subsurface and/or in subaqueous enclaves within subaerial settings, chemotrophic, and anaerobic, as inferred for the early Earth, and potentially associated with hydrothermal systems (e.g., Gogarten-Boekels et al. 1995; Abramov and Mojzsis 2009; Westall et al. 2015a, 2015b, 2018; Djokic et al. 2017; Michalski et al. 2017). Moreover, while impact processes can damage organic material, impacts can also result in habitable conditions and impact-generated hydrothermal systems can preserve evidence of life that colonized the system subsequent to impact (e.g., Edwards and Powars 2003).

Earth-generated hydrothermal environments include subaerial hot-spring aprons, mounds, and fumaroles, as well as shallow and deep-sea vents (black and white smokers), and subaqueous lacustrine spring-vents and hot-water fluvial systems (Fig. 1.8). In continental hydrothermal settings, two different endmember products may manifest depending on thermal fluid composition (1) acidic alteration of existing rocks to form fumaroles, silica residue, clays, and other alteration minerals, and (2) deposition of new chemical sedimentary rocks (e.g., silica sinter from alkali chloride and acid-sulfate-chloride fluids of neutral to slightly acidic pH, or travertines from bicarbonate fluids; Renaut and Jones 2011). Both of these endmember types have been inferred from data collected by *Spirit* at Columbia Hills (Squyres et al. 2008; Ruff et al. 2011). While not all these Earth-based hydrothermal systems have known direct analogs on Mars (e.g., large volumes of carbonate associated with the Lost City type vents of the mid-Atlantic Ridge; large sulfide-rich "black smoker" deposits), they illustrate a range of conditions and settings in which microbes dominate the base of the food chain at above-ambient temperatures. Most importantly, these are typically mineralizing systems where biological information is captured and preserved by rapid mineral precipitation (e.g., Walter and Des Marais 1993; Farmer and Des Marais 1999; Van Dover 2000; Campbell et al. 2015a, 2015b) (Table 1.10).

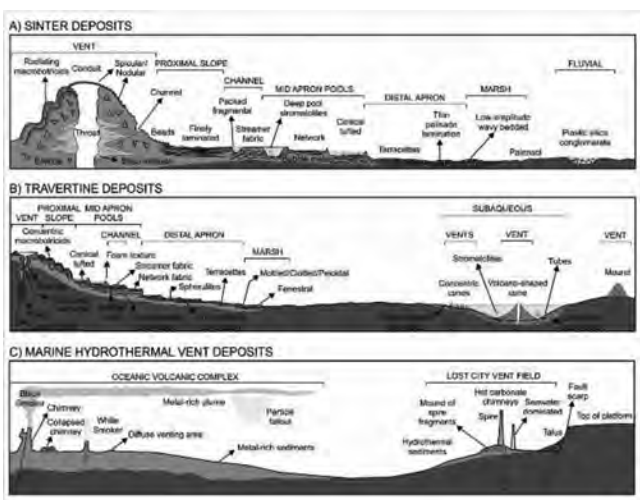

Fig. 1.8. Schematic cross sections of Earth-based, shallow, surface hydrothermal environments. (a) Siliceous hot-spring deposits (sinter) of near-neutral pH, alkali chloride fluid composition, and (b) carbonate hot-spring deposits (travertine)) (Guido and Campbell 2011; Renaut and Jones 2011). Textural biosignature distribution patterns occur along temperature gradients from proximal vent areas (~100 °C) to distal apron/flank settings (~25–30 °C). Marine hydrothermal vents (c) produce even steeper temperature gradients, from ~400 °C at black smoker vent emission points to ambient seawater temperatures short distances away from the vents (Van Dover 2000).

1.2.3 Why Returned Sample Studies Are Important for Sub-Objective 1.2

Much has been learned of Martian hydrothermal systems from orbit, assuming that mineral assemblages produced by such systems on Mars are comparable with those of analogous systems on Earth. Similarly, data from rovers, particularly *Spirit* (Fig. 1.7) have given us insight into chemical processes operational in a fossil hydrothermal system. Despite these advances, many questions are still outstanding and can only be addressed by detailed fine-scale analyses using complementary techniques. For example, hydrothermal systems on Earth host microbial communities, but detection of biosignatures in fossilized hydrothermal systems requires multiple lines of evidence taken from high-resolution imagery matched with elemental and isotopic data. Even then, identification of ancient biosignatures is not straightforward, and generates

Table 1.10. Key open questions for Sub-Objective 1.2: Understanding Martian hydrothermal systems.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.2
What is the spatiotemporal distribution of hydrothermal events throughout Mars' history, both magmatic and impact-related? Has this collectively been geographically extensive enough over long enough intervals to sustain habitable environments with liquid water that were suitable for life?
How have hydrothermal processes affected Mars' climatic, hydrologic, and lithospheric domains? In what manner do hydrothermal processes link these features of the planet through time?
Can models for recognition of hydrothermal edifices and deposits on Mars be refined in a nested hierarchy of observations, from orbital to outcrop to sample to micron-scale laboratory analyses?
Would Martian hydrothermal processes and products be expected to be similar to or different from those on Earth? For example, sinter like deposits have been identified from Columbia Hills and compared to terrestrial hot-spring deposits at El Tatio, Chile (Ruff and Farmer 2016), while large fractures and extensive fracture-parallel ridge deposits have been found in Magaritifer Terra (Thomas et al. 2017). The latter may have no equivalent on Earth. What do these types of putative hydrothermal settings tell us about Mars' geologic history?
Do the ages of the hydrothermal systems overlap with the water-rich interval of Mars' evolution as a planet?

much vigorous debate, especially for early Archean deposits (e.g., Brasier et al. 2002, 2005; Schopf et al. 2002; Schopf and Kudryavtsev 2012; Marshall et al. 2011; Nutman et al. 2016; Dodd et al. 2017). Another justification for returned samples is the need to determine highly precise ages of different layers or structures within the material. This would enable inferences to be made about the scale and rate of hydrothermal processes—measurements not possible in situ on Mars.

1.2.4 Sample Investigation Strategies to Achieve Sub-Objective 1.2

The key investigation strategies and samples proposed below are intended to establish the geologic context of at least one Martian hydrothermal environment, which would help to constrain past habitability and assess the potential for biosignature capture and preservation (see Objective 2). A key strategic element is to focus sampling from environments that represent the highest potential for delimiting both past habitability and state of preservation (e.g., conditions producing lagerstätte, or exceptional preservation and which protect original biosignatures from postdepositional obliteration by diagenetic and/or environmental processes) (Hays et al. 2017). Hydrothermal environments are advantageous targets because terrestrial examples are replete with biology at all scales and across many types of gradients (Fig. 1.8). Their mineralization capability has the potential to shield biosignatures in a robust, in situ mineralogic tomb that could be amenable to both detection and long-term preservation. We propose five specific investigation strategies and 14 measurements on returned samples from Martian hydrothermal deposits.

The search for hydrothermal biosignatures would initiate with rover cataloging of spectral signatures in aqueous-influenced sedimentary rocks/minerals at the site, followed by selection of areas for targeted in situ observations that could produce spatially integrated maps of mineralogy and macro- and microtextures. Mapping the site of aqueous deposits would help test if facies (i.e., environmental) models of Earth's hydrothermal systems provide appropriate analogs for mineralized hydrothermal deposits on Mars. A recent example highlighting this approach is illustrated by study of the hydrothermal opaline silica deposit discovered by *Spirit* rover in Gusev Crater interpreted as fumarole related or near-neutral pH alkali chloride sinter (Squyres et al. 2008). It contains unusual, knobby, digitate structures unlikely to have been formed by wind erosion (Ruff et al. 2018), and which have been inferred as a morphological potential biosignature (PBS) (Fig. 1.7). Comparison with siliceous hot-spring deposits (sinter) at El Tatio geothermal field in Chile reveal close similarities with respect to textures (Figs. 1.7a–h) and mineral spectra (Fig. 1.7i) (Ruff and Farmer 2016), thereby strengthening the environmental framework and interpretation of the possible biotic nature of the structures. In particular, the knobby silica features at El Tatio constitute microstromatolites, entombing bacterial filaments within spring-derived hydrothermal silica (Figs. 1.7g and 1.7h). In analogous features forming in New Zealand hot springs, microbial filament-rich horizons alternate with nonfilamentous laminae of homogeneous silica that themselves constitute silicified, microbially excreted EPS (exopolymeric substance) (Handley et al. 2005, 2008). In other words, the entire siliceous digitate structure is microbial in origin.

We propose five specific investigation strategies and 14 sets of measurements on samples returned from a Martian hydrothermal system (Table 1.11).

<u>Investigation Strategy 1.2A</u>: Identify hydrothermal facies that reflect primary differences in deposit formation temperature, due to cooling and degassing of fluid discharge along a gradient with respect to proximity to the vent source.

Terrestrial hydrothermal systems facies models (e.g., Fig. 1.8) predict locales along temperature gradients

Table 1.11. Summary of sample-related investigation strategies to understand an ancient Martian hydrothermal system.

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.2		
1	**Geological environment(s)**	**Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.**
1.2	Hydrothermal	Understand an ancient Martian hydrothermal system through study of its mineralization products and morphological expression.
IS 1.2A	Identify hydrothermal facies that reflect primary differences in deposit formation temperature, due to cooling and degassing of fluid discharge along a gradient with respect to proximity to the vent source.	
IS 1.2B	Reconstruct the character of the fluids of the paleo-hydrothermal system. Determine the primary environmental and geochemical parameters at the time the system was active.	
IS 1.2C	Reconstruct how the depositional system changed over time, and as a function of position within the system.	
IS 1.2D	Determine the age of the hydrothermal system, and the duration and rate of water flow.	
IS 1.2E	Investigate the possibility of postdepositional modification/fluids, and interpret those processes.	

from vent-to-peripheral hydrothermally influenced areas where signs of life are concentrated. Therefore, sampling along such gradients may be selective and targeted to maximize potential to locate potential biosignatures within a clear paleoenvironmental framework. In particular, microbial life adapted to terrestrial hydrothermal environments is limited by an optimum maximum growth temperature of 80 °C (Madigan et al. 2006), with survival at up to 122 °C (Takai et al. 2008). In continental hot springs, for example, ideal sites for sample collection would be in the middle- to low-temperature apron suites (~55–25 °C) of hydrothermal materials (Fig. 1.8a). Not only are the mineralized microbial deposits thickest there but the microorganisms also tend to become entombed more rapidly and completely, especially if mineralization was early in diagenesis (e.g., Campbell et al. [2015a, 2015b] and references therein). In fact, the Columbia Hills silica features are interpreted to have formed in this type of setting, in inferred-Noachian age, hot-spring discharge channels morphologically and mineralogically similar to high-elevation, saline, low-flow hot springs at El Tatio geothermal field, Chile (Ruff et al. 2011; Ruff and Farmer 2016). Furthermore, shallow subsurface, lateral zones (i.e., within sediments infused with percolating hydrothermal fluids; Rasmussen 2000; Westall et al. 2015a, 2018) could be important additional sampling targets. Thus, we may expect to see systematic trends in deposit thickness (as mounds and lateral thinning of beds away from vent point sources) and textural types, and/or systematic shifts in isotopic fractionation patterns in values for oxygen and silicon isotopes, and/or downslope changes in mineralogy, etc. Thus, returned samples would ideally—and as a priority—include suites that represent temperature gradients away from spring-vent sources (Fig. 1.8), particularly in mid- to distal apron settings at moderate to tepid thermal fluid temperatures (~60–30 °C in Earth siliceous hot-spring [sinter] analogs), where microbial mat development is also most prominent. Thus, target sample suites could be focused on this portion of a given paleo-hydrothermal deposit.

Table 1.12 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.2A and move toward understanding of a Martian hydrothermal system.

Table 1.12. Samples and measurements implied by Investigation Strategy 1.2A.

Samples identified to advance Investigation Strategy 1.2A:

- A suite of hydrothermal samples and/or altered host rocks representing decreasing paleotemperature with distance (e.g., proximal to distal) from the hydrothermal vent, in lateral and vertical stratigraphic context.

Measurements identified to advance Investigation Strategy 1.2A:

- Identify spatial and temporal variability in the mineralogy, chemistry, texture, grain size, and grain shape of each defined facies formed, or modified, by hydrothermal activity. This will delineate the extent of the hydrothermal footprint in time and space.
- Measure the stable isotopic compositions of oxygen and silicon in primary rocks and minerals to look for systematic trends with respect to facies and minerals that may reflect thermal gradients.
- Spectroscopy/mapping of rock sample surfaces (e.g., Raman), which can be used for paleotemperature estimates.
- Detailed examination of mineral fabrics and compositions (e.g., with SEM/EMPA) to evaluate consistency with low-temperature hydrothermal conditions at the Martian surface.

***Investigation Strategy 1.2B:* Reconstruct the character of the fluids of the paleo-hydrothermal system. Determine the primary environmental and geochemical parameters at the time the system was active.**

The often-changing nature of hydrothermal fluids in terrestrial environments reflects regional magmatic-crustal-hydrologic interactions and climate (e.g., Guido and Campbell 2014; Sillitoe 2015). Subsurface hydrothermal fluids feeding surface geothermal manifestations range from near-neutral alkali chloride waters tapping deep hot (>175°C) reservoirs of circulating heated groundwaters, to acidic steam condensates dissolved in groundwaters, to mixed acid-sulfate-chloride and bicarbonate fluids (Fig. 1.9) (Renaut and Jones 2011). Commonly in Earth-analog hydrothermal paleoenvironments, textural variation in lithologies, along with particular mineral distributions, provide an important framework for identifying environmental parameters controlling microbial community composition and biogeochemical activity. Specifically, returned samples would allow a detailed assessment of microscale habitability based on contemporaneous evidence for (1) primary aqueous mineralogy, (2) rapid mineral precipitation, and 3) pervasive early cementation by a stable mineral phase. In terrestrial hot springs, fluid compositional and pH variations (e.g., alkali chloride, acid sulfate, bicarbonate, iron, acid-sulfate-chloride, hydrogen sulfide) can be extreme over short distances, providing important redox-potential gradients across which biogeochemical cycles operate (Jones and Renaut 2007, 2012).

Thus, important biologically relevant information on variable fluids of the hydrothermal system could be identified in the returned sample suite, potentially collected within a small area amenable to mission

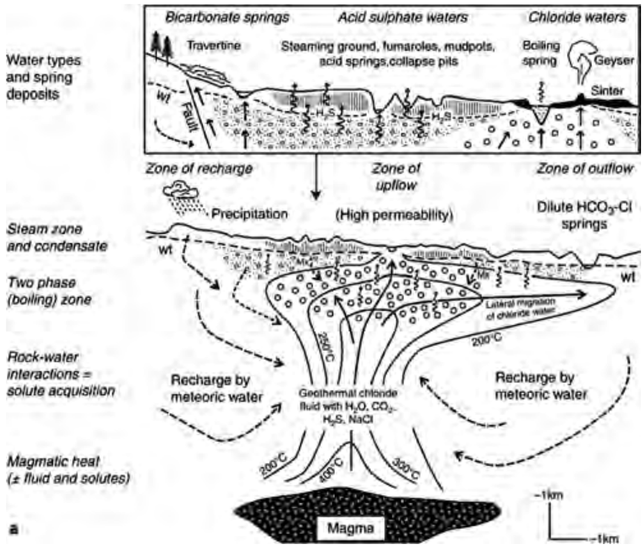

Fig. 1.9. Continental terrestrial hot-spring fluid types formed by magmatic heating and circulation of mainly meteoric waters that pick up solutes from water–rock interactions to form chloride reservoir-derived fluids (up to 400°C), with variable amounts of dissolved H_2S and CO_2, which may (1) rise directly to the surface in upflow zones to form near-neutral alkali chloride geysers and hot springs; (2) undergo two-phase boiling during ascent and pressure release to form acidic steam condensate-fed mud pools and fumaroles; (3) feed bicarbonate springs with dissolved CO_2 at the margins of the geothermal field (from Renaut and Jones 2011).

engineering parameters and objectives. A relevant returned sample suite could help constrain the stability and paragenesis of bioessential elements to determine if it would be reasonable for them to have existed in that environment at the time of deposition, whether their concentrations are significantly above average, and if associated minerals preserve evidence of biogeochemical cycling. The measurement of stable isotopic compositions (e.g., of C, H, N, O, S) in organic compounds or minerals in context with known isotopic reservoirs enables the search for signatures that are inconsistent with abiotic processes. Stable isotope measurements should be coupled to distribution within samples (e.g., mapping in polished sections) at millimetric to nanoscale.

Table 1.13 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.2B and move toward understanding of a Martian hydrothermal system.

***Investigation Strategy 1.2C:* Reconstruct how the depositional system changed over time, and as a function of position within the system.**

Stratigraphic analyses initiated with rover exploration, and refined by petrologic and paragenetic analyses in returned sample suites, would delineate the evolutionary history of the hydrothermal deposit and allow predictions to be made with respect to locating types of preserved biologic signatures, as well as confirming rover mapped distributions with microfacies analysis, and evaluating quality of preservation (Fig. 1.10). Furthermore, hydrothermal systems are known to change compositional characteristics rather rapidly, e.g., reflecting a volcanic eruption (e.g., Simmons et al. 1993), or change in the hydrologic-climate cycle (e.g., Drake et al. 2014; Guido and Campbell 2014, 2017). Thus, hydrothermal deposits could serve as paleoenvironmental dipsticks, reflecting fluctuating shifts in pH, Eh, water table, water-rock interactions, and PBS community composition. Important samples to target would be transitions in mineral and textural suites.

Table 1.13. Samples and measurements implied by Investigation Strategy 1.2B.

Samples identified to advance Investigation Strategy 1.2B:

- A suite of hydrothermally generated deposits and/or hydrothermally altered host rocks representative of the range of chemistry and mineralogy within the potential hydrothermal system.

Measurements identified to advance Investigation Strategy 1.2B:

- Measure geochemical proxies for salinity/composition of fluid inclusions in primary precipitates and secondary pore-filling cements that formed or were modified by hydrothermal processes.
- Measure the stable isotopic compositions (e.g., O, S, C, N, and Sr) of primary minerals and gases (e.g., CO_2, SO_2, H_2S, CH_4, H_2, etc.) trapped in fluid inclusions.
- Measure bioessential elements (e.g., C, H, N, O, P, and S, other than compounds containing these elements in the atmosphere), as well as any bioessential trace elements (e.g., Fe, Zn, Co, Ni), and concentrations of potential electron donors in host rock or soil/paleosol samples associated with hydrothermal activity.
- Measure mineral suites to determine mixed valence states for redox energy and isotopic proxies of specific redox couples (e.g., $\delta^{34}S$, $\delta^{56}Fe$) expected in hydrothermal systems.

Table 1.14 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.2C and move toward understanding of a Martian hydrothermal system.

***Investigation Strategy 1.2D:* Determine the age of the hydrothermal system, and the duration and rate of water flow.**

It is important to establish the age of the hydrothermal system and whether it overlaps with the

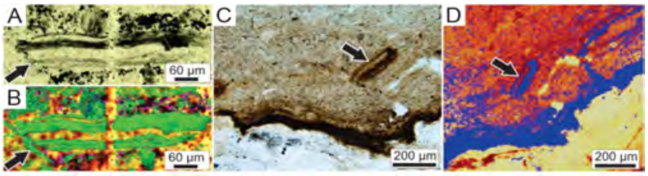

Fig. 1.10. Mapping via petrographic thin section and in situ, high-resolution Raman spectroscopic analyses of hydrothermal minerals and fossilized microbial mat laminates in (A, B) a shallow marine hydrothermal paleoenvironment preserved in hydrothermal silica from early Archean chert in South Africa (3.3 Ga), and (C, D) Late Jurassic (150 Ma) sinter from Argentina. Arrows indicate mat laminate fragments. Organic carbon may be preserved even in extremely old hydrothermal silica (e.g., A, B), or replaced by later minerals (e.g., anatase replacement of mat laminates in C, D). However, despite possible loss of organic carbon, preferential mineralization of previously carbonaceous textures can still preserve evidence of biogenicity. Raman colors: green—carbon, yellow/orange/red—quartz, magenta—muscovite, blue—anatase (low-temperature TiO_2 mineral). Modified from Westall et al. (2015b).

water-rich interval of Mars' evolution as a planet, a time when life is most likely to have been present. Returned samples would be subjected to quantitative geochronologic analysis, placing the hydrothermal system into Mars' climatic, igneous, and paleohydrologic history. For example, alunite and jarosite are common hydrothermal alteration products in epithermal systems and may be suitable for K-Ar and/or ^{40}Ar-^{39}Ar dating and, in combination with stable isotopes, may provide information about paleoclimate (e.g., Stoffregen et al. 2000), aiding reconstruction of Mars' magmatic-hydrologic-climatic evolution. Furthermore, nested investigation of textures (physical sedimentary and preserved biologic structures) of hydrothermal deposits, their sedimentology, bedding geometries, and stratigraphic relationships would together aid estimates of channel volumes, mound sizes, and the depth of hydrothermal ponds over the entire hydrothermal system—serving as proxies for volume and duration of thermal fluid flow/accumulation (e.g., Guido and Campbell 2014), and thus illuminating primary controlling factors on the character and distribution of PBSs. Key samples would be rocks with datable mineral suites and textural-mineral types reflecting relative amount of fluid flow in the paleo-hydrothermal system.

Table 1.15 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.2D and move toward understanding of a Martian hydrothermal system.

Investigation Strategy 1.2E: ***Investigate the possibility of postdepositional modification/fluids, and interpret those processes.***

This investigative component addresses preservation quality of preserved biologic signatures. Besides postdepositional geological activity, the relative timing of hydrothermal alteration overprints and other late diagenetic events have significant impacts on whether biosignatures are expected to be pristine, or whether they have been modified and could still be distinguishable. For example, microbial macro-textures commonly are preserved in siliceous and calcareous hot-spring deposits on Earth. However, high-quality, microscale preservation of biosignatures—producing convincing fossil biosignatures—depends on timing of mineralization (e.g., early silicification; Campbell et al. [2015a, 2015b] and references therein; Djokic et al.

Table 1.14. Samples and measurements implied by Investigation Strategy 1.2C.

Samples identified to advance Investigation Strategy 1.2C:
- Hydrothermally generated/altered rocks sampling interbedding, crosscutting, and/or overgrowth relationships from different stratal positions within the hydrothermal system, which for impact-generated breccias naturally provide a diverse assemblage from various levels within the crust.

Measurements identified to advance Investigation Strategy 1.2C:
- Use multiple methods (e.g., light microscopy, Raman, XRD, EMPA, FTIR, and other methods) to study hydrothermal deposits and host rocks to place minerals and microtextures into a broader stratigraphic context; determine the relative age and crosscutting relationships of minerals, fabrics, and structure, linking established outcrop scale to the microscale. Produce a paragenetic sequence of the complete history of the hydrothermal deposit.

Table 1.15. Samples and measurements implied by Investigation Strategy 1.2D.

Samples identified to advance Investigation Strategy 1.2D
- A suite of hydrothermally generated/altered rocks representative of the range of rocks fitting a hypothesized age model within the potential hydrothermal system. For exposure ages, use mineralogy to constrain burial depth and timing of exposure history of local outcrops.

Measurements identified to advance Investigation Strategy 1.2D:
- Assess system size, and relative fluid volume and duration of fluid flow.
- Measure the radiometric ages (Rb-Sr, K-Ar, and $^{40}Ar/^{39}Ar$) of the minerals with permissible mineralogy (e.g., jarosite, calcite, alunite, etc.)
- Measure cosmogenic nuclides (e.g., but not limited to, ^{3}He, ^{10}Be, ^{21}Ne, ^{38}Ar) of surface samples to determine exposure age and erosion rate.

Table 1.16. Samples and measurements implied by Investigation Strategy 1.2E.

Samples identified to advance Investigation Strategy 1.2E

- Rocks, especially clays, that potentially show evidence of late-stage diagenetic processes such as hydrothermal alteration, superimposed on the hydrothermal system.

Measurements identified to advance Investigation Strategy 1.2E:

- Evaluate evidence for paleo-water table fluctuations, and timing of fractures and history of infilling of fractures to form veins and differential concentration of hydrated sulfate and clay minerals.
- In constructing a paragenetic sequence of the history of a given hydrothermal deposit (see also 1.1C), differentiate cements and other paragenetic events that are pore-filling (i.e., late diagenetic), search for evidence of dissolution and/or extensive replacement, or recrystallization of primary phases, and examine the mineral composition for evidence of suites of hydrothermal alteration minerals.

2017), type of overprinting (e.g., acidic fluids with drop in phreatic level, or regional late silicification), and whether late diagenetic processes have been local or regional in extent (e.g., Walter et al. 1996; Guido and Campbell 2009, 2011, 2017; Campbell et al. 2018). Mapping diagenetic stage (e.g., Lynne and Campbell 2003; Jones and Renaut 2007), textural quality, and geochemical concentrations of relevant minerals and elements—at the microbial scale (e.g., Westall et al. 2015a, 2018)—may be achieved with key returned samples.

Table 1.16 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.2E and move toward understanding of a Martian hydrothermal system.

1.3 Sub-Objective 1.3: Understand the Rocks and Minerals Representative of a Deep Subsurface Groundwater Environment

UNDERSTAND A DEEP SUBSURFACE GROUNDWATER ENVIRONMENT	
Why is this objective critical?	*A key input into interpreting the history of water on Mars; search for life.*
Which are the most important samples?	*One or more suites of rocks from all units in the stratigraphy with evidence of groundwater flow, including altered and veined zones, including samples that represent time evolution or distance.*

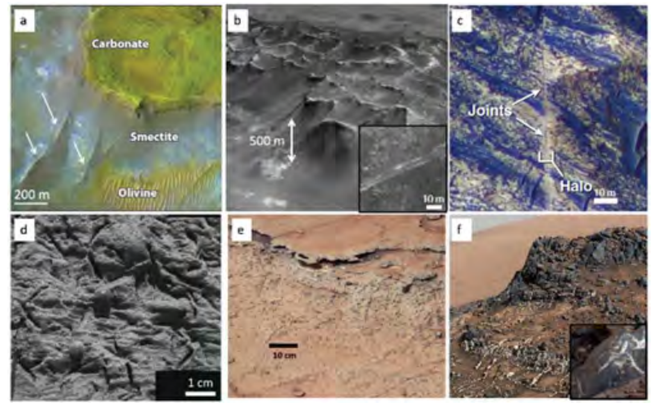

Fig. 1.11. (a) Groundwater-mineralized Fe/Mg phyllosilicate filled fractures in a >300 m thick section (Saper and Mustard 2013) beneath olivine-carbonate-rich rocks formed in a shallow aquifer; (b) 500 m penetrative alteration of the NE Syrtis sedimentary sulfate deposits with isopachous jarosite-bearing ridges (Quinn and Ehlmann 2018); (c) haloes indicate groundwater flow through Valles Marineris sediments (Okubo and McEwen 2007); (d) microscopic imager data at Terra Meridiani shows multiple generations of groundwater mineral precipitation and dissolution, indicated here by crystal vugs, (McLennan et al. 2005); (e) dark nodules and sulfate veins indicate multiple generations of groundwaters in rocks initially formed as Gale lake sediments (Siebach et al. 2014); (f) multiple generations of thick veins, including penetrative fractures indicate groundwaters in deeply buried rocks at Gale Crater (Mastcam image from sol 938; Kronyak et al. 2017).

1.3.1 Introduction and Current State of Knowledge

Groundwater aquifers on Mars, an important source and sink of surface waters, may represent some of the longest lived, potentially habitable environments on the planet. Chemolithotrophs, organisms that depend not on sunlight energy, but on inorganic chemical reactions for energy, are uniquely suited to life in the subsurface. The subsurface as a habitat on Mars was postulated because of the potential for water to persist and the protection provided from inhospitable surface conditions (Fig. 1.11) (Gold 1992; Boston et al. 1992; Ehlmann et al. 2011a; Schulte et al. 2006; Michalski et al. 2013, 2017). On Earth, terrestrial mafic and ultramafic igneous aquifers and sedimentary aquifers have been found to be significant microbial habitats (e.g., Ghiorse and Wilson 1988; Stevens and McKinley 1995; Whitman et al. 1998; Onstott et al. 2009; Kallmeyer et al. 2012; Schrenk et al. 2013; Osburn et al. 2014; Hug et al. 2015; Rempfert et al. 2017). On Mars, the rock record for past groundwater aquifers is found globally, traceable by spatial patterns in the type and distribution of hydrated minerals (e.g., Murchie et al. 2009; Ehlmann et al. 2011a; Carter et al. 2013) and found by missions in situ (Grotzinger et al. 2005; McLennan et al. 2014) as predicted by modeling (Andrews-Hanna and Lewis 2011; Horvath and

Andrews-Hanna 2017). Exposed rocks from such deep groundwater aquifers on Mars are accessible to be explored, sampled, and investigated to understand their geologic history and potential habitability. Some even postulate that such aquifers may continue to exist to the present (e.g., Grimm et al. 2017).

Evidence for deep subsurface groundwater on Mars is found from orbit, in situ (Fig. 1.11) and in the meteorite record. The first indication of fluid reservoirs in Mars's subsurface came from the meteorite record. Meteorites record the interaction of erupted lavas with a hydrosphere through the presence of hydrated minerals present at minor to trace amounts (e.g., phyllosilicates, carbonates, sulfates) (e.g., J. C. Bridges et al. 2001). These phases are even present in the Martian meteorites that crystallized at a time after ~1.3 Ga (Nyquist et al. 2001) during which the Mars surface environment was thought to be cold and arid. This was the first pointer to fluid reservoirs in the subsurface, and these relatively late reservoirs in Mars time are poorly understood. At the Meridiani Planum landing site, shallow playa lakes fed by Hesperian groundwaters were discovered by the *Opportunity* rover (e.g., Squyres et al. 2004; Grotzinger et al. 2005). Multiple episodes of groundwaters are indicated by petrological relationships between hematite concretions, sulfate crystals, empty crystal molds, and occluded pore space in sand-sized rocks (e.g., Fig. 1.11d) (McLennan et al. 2005; Tosca et al. 2005), and the age is constrained to be Hesperian from geological relationships. The last stages of waters evaporating near the surface were likely not habitable due to acidity and low water activity (Tosca et al. 2008), though the groundwaters prior to oxidation and evaporation would have been habitable. Elsewhere from orbit, other basins host distinctly sedimentary sulfate deposits, hundreds of meters thick, with fracture fills indicative of extensive groundwater flow (e.g., Lichtenberg et al. 2010; Thollot et al. 2012; Quinn and Ehlmann 2018). Like at Meridiani, the explorations of the Curiosity rover in Gale Crater show multiple episodes of interaction with groundwater following initial deposition in a lake (Figs. 1.11e and 1.11f) (e.g., Grotzinger et al. 2014, 2015; McLennan et al. 2014; Vaniman et al. 2014; Siebach et al. 2014). Unlike at Meridiani, the waters at Gale were mostly neutral to alkaline, forming Mg smectites, magnetite, gypsum, and other phases in multiple phases of water activity that may have represented habitable environments (Bristow et al. 2015; Stack et al. 2014; Siebach et al. 2015). The last stages of groundwater at Gale Crater may have been quite recent, as indicated by dates of <2 Ga in jarosite in sandstones (Martin et al. 2017). Finally, throughout the Noachian crust of Mars, mineralized ridges with phyllosilicates and Fe/Mg smectite–chlorite–zeolite mineral assemblages point to circulating groundwaters, exposed in numerous locations by faulting, erosion or impact (Fig. 1.11a) (Ehlmann et al. 2011a, 2011b; Thollot et al. 2012; Saper and Mustard 2013; Kerber et al. 2017). The occurrence of hydrated phyllosilicates in association with impact craters may be evidence for impact-induced hydrothermal flow and groundwater circulation (e.g., Osinski et al. 2013; Tornabene et al. 2013). Interrogation of rocks representative of subsurface aquifers would provide unique insights into the primary geologic process recorded by the rock record (Objective 1), the potential habitability of groundwater systems, and potential biosignatures from microorganisms inhabiting these aquifers.

1.3.2 Key Open Questions for Sub-Objective 1.3

Groundwater aquifers were clearly a key component of Mars's hydrologic and climate cycle. Attributes of groundwater aquifers that can be further constrained by examination of rocks include the sources, timing, and persistence of groundwaters over different parts of the planet; the chemistry and temperatures of the groundwaters; their communication with the surface and/or with magmas; the evolution of the chemistry of groundwaters; the role of groundwaters in Mars's long-term geochemical cycling; the habitability of the subsurface; and groundwater aquifer rocks as a host for biosignatures of past life (Fig. 1.12).

Are groundwaters part of a potentially globally connected hydrologic system (Fig. 1.13) (e.g., Clifford 1993; Clifford et al. 2010; Andrews-Hanna and Lewis 2011) or are groundwaters partitioned into smaller subbasins? This is part of the larger question of the Martian hydrological cycles: At the global scale was the system vertically integrated or horizontally stratified? (Head 2012) In contrast to Earth's oceans, which have been present continuously since >4 Ga, Mars may have had an episodic northern ocean fed by outflow channels

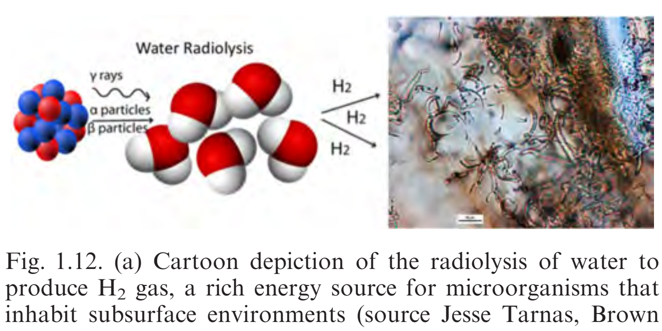

Fig. 1.12. (a) Cartoon depiction of the radiolysis of water to produce H_2 gas, a rich energy source for microorganisms that inhabit subsurface environments (source Jesse Tarnas, Brown University). (b) Microbial trace fossils in 14.8 million-year-old impact glass from the Ries Impact Structure, Germany (Schmieder et al. 2018; Sapers et al. 2014)

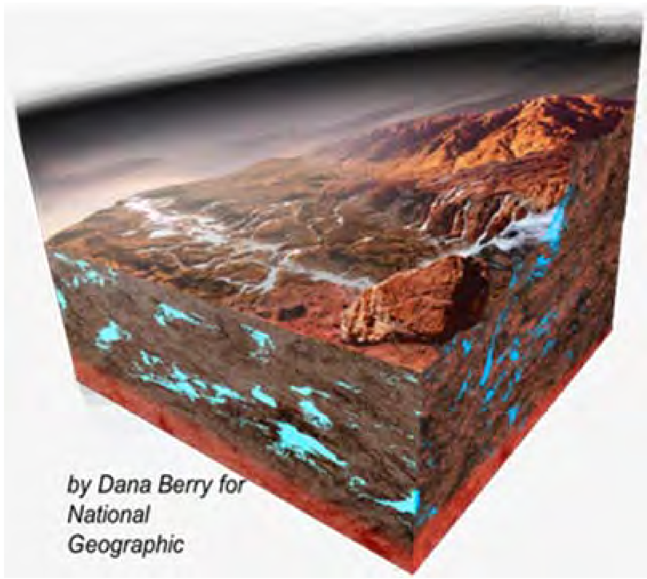

Fig. 1.13. Concept of the surface and subsurface of Mars ~4 billion years ago, showing a surface hydrological system connected to subsurface groundwater systems. Figure by Dana Berry for National Geographic.

(e.g., Tanaka 1997), but there is scant geologic evidence that Mars had a northern ocean in continuous existence for billions of years (e.g., Pan et al. 2017). However, groundwaters may have been persistent over greater time periods (e.g., Martin et al. 2017). While mineralogic evidence for water–rock interaction was widespread, geochemical evidence does not show the leaching characteristic of open-system water–rock reactions. This is a distinctly different situation from that of Earth where weathering driven by a surface hydrologic cycle has delivered sediments to ocean basins for all of Earth history. Instead, on Mars, surface runoff and groundwaters were crucial in periodically generating lakes, which in their later episodes were fed by groundwaters alone, facilitating diagenesis (Goudge et al. 2015; Michalski et al. 2015). Thus, investigations of deep groundwaters naturally grade to those of sediments from surface waters in Investigation 1.1, where diagenesis of the sediments is by groundwaters, and surface hydrothermal systems in Investigation 1.2, which are the outflows of the warmest groundwaters (Table 1.17).

Table 1.17. Key open questions for Sub-Objective 1.3: Understanding deep subsurface groundwaters.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.3
What were the timing of and water sources sustaining the groundwaters of Mars?
What was the chemistry and temperatures of groundwaters on Mars and did these evolve with time?
Did groundwaters communicate with the atmosphere and with magmas and play a major role in Martian geochemical cycles?
Do Mars's groundwaters represent local water sources or a globally connected hydrologic system?
What was the habitability of groundwater aquifers?
Do rocks from groundwater aquifers host biosignatures of past life?

1.3.3 Why Returned Sample Studies Are Important for Sub-Objective 1.3

From orbit, the record of groundwaters reveals more mineralogical diversity than has yet been interrogated by landed missions, which have not yet interrogated sections of intact Noachian rock. Chemically closed system alteration is indicated in most Noachian terrains with Fe/Mg smectites and chlorites, illite, zeolites, silica, and serpentine assemblages (Mustard et al. 2008; Ehlmann et al. 2010, 2011b; Carter et al. 2013), although it is not possible to discern from orbit whether these clay-bearing rocks were igneous or sedimentary (for discussion, see Bandfield et al. 2013). The constituent minerals of these rocks from various places on Mars indicate groundwater alteration at conditions ranging from ambient to hydrothermal (Ehlmann et al. 2011a, 2011b). The highest temperature phase detected to date is prehnite (formation temperatures constrained to ~200–400 °C; Frey and Robinson 1998); amphiboles that would indicate higher temperatures are conspicuously absent (Carter et al. 2013). In several locations, mineralized veins indicate episodes of groundwater flow through sections of phyllosilicate-bearing rock that are 100s of meters thick (Saper and Mustard 2013). Samples collected in situ with geological context at the meter scale and below to understand the chemistry, timing, episodicity, and longevity of groundwater availability are thus crucial to understanding Martian climate and interpreting habitability.

1.3.4 Sample Investigation Strategies to Achieve Sub-Objective 1.3

There are four main investigative strategies proposed to understand the geologic processes on Mars that have affected subsurface rocks in contact with groundwaters. To understand the extent of subsurface water/rock interaction we would investigate the morphologies and mineral assemblages suggestive of such processes. We would characterize the physicochemical conditions of the fluids and the water/rock reactions to assess the potential habitability, determine the source of fluids, and interpret the reactions governing mineral precipitation. We would

Table 1.18. Summary of sample-related investigation strategies to understand an ancient Martian deep subsurface groundwater environment.

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.3		
1	**Geological environment(s)**	**Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.**
1.3	Deep subsurface groundwater	Understand the rocks and minerals representative of a deep subsurface groundwater environment.
IS 1.3A	Interpret the morphologic features and minerals resulting from groundwaters in igneous and sedimentary host rocks to understand the extent of groundwaters, their transport, and their episodicity.	
IS 1.3B	Determine the physicochemical conditions of water-rock interaction and assess habitability.	
IS 1.3C	Determine the source of fluids and abiotic or biotic reactions governing mineral precipitation.	
IS 1.3D	Determine the time evolution of the groundwater system and chemical reactions.	

examine the petrological relationships between phases to determine the evolution of the groundwater system and fluid chemistries with time.

We propose four specific investigation strategies and 16 sets of measurements on samples returned from a Martian groundwater system (Table 1.18).

***Investigation Strategy 1.3A:* Interpret the morphologic features and minerals resulting from groundwaters in igneous and sedimentary host rocks to understand the extent of groundwaters, their transport, and their episodicity.**

At the landing site, the stratigraphic context and host rock can only be discerned by measurements at meter scale and lower. At present, for most minerals inferred from orbit to form from groundwaters, it is not known whether the host rock is igneous or sedimentary, nor can its local stratigraphy be determined. The timing(s) of episodes of groundwater mineralization are thought to be ancient (>3 Ga), though at least one in situ date implies younger groundwaters (Martin et al. 2017) and timing is constrained only by crosscutting relationships with other stratigraphic units. Thus, basic first-order questions about Martian groundwater are the focus of the first investigation. These questions include the nature of the host rock, the extent of aqueous alteration/interaction with the host rock, the style of transport (pore space versus fracture-confined), and episodicity.

Table 1.19 summarizes the type of samples that should be collected, and the associated measurements

Table 1.19. Samples and measurements implied by Investigation Strategy 1.3A.

Samples identified to advance Investigation Strategy 1.3A:

- A suite of rocks from all units with evidence of groundwater flow, representative of a variety of depths within the stratigraphy. Features indicative of groundwater flow include mineralized fractures or ridges, diagenetic concretions, zones with color change indicating leaching, and/or cements and should be sampled along with adjacent host rock.

Measurements identified to advance Investigation Strategy 1.3A:

- Analyze stratigraphy and petrography to determine the protolith of aquifer rocks (igneous or sedimentary and the local stratigraphy).
- Examine the mineralogy of host rock and veins/vugs/fractures to identify evidence of chemical interaction with waters and the extent to which primary minerals have been altered by groundwater flow.
- Characterize the petrology to understand crosscutting relationships and the timing of groundwaters relative to other geological events.
- Evaluate the number of distinct episodes of groundwaters by examining rocks with crosscutting relationships between zones of distinct mineralogy or morphology.
- Determine formation ages of the groundwater host rock as well as the fluid-precipitated minerals (e.g., carbonate, jarosite, some phyllosilicates suitable for dating using radiogenic isotopes).

required in order to carry out Investigation Strategy 1.3A and move toward understanding of a Martian subsurface groundwater systems.

***Investigation Strategy 1.3B:* Determine the physicochemical conditions of water–rock interaction and assess habitability.**

Key water properties, including temperature, pH, Eh, aH_2O, and ion activities, can be derived by identification of mineral assemblages. On Earth, the currently recognized temperature limits for metabolic activity ranges from −25 °C for microorganisms in permafrost (Mykytczuk et al. 2013) to 122 °C for a methanogen isolated from a deep-sea vent plume (Takai et al. 2008). Thus, understanding the temperature range of Martian groundwaters is important. Understanding sources of heat—geothermal, magmatic, impact, or simple climate change—is also important for understanding the groundwater system. The minerals observed in fractures will change as the groundwater system evolves and multiple generations of minerals are precipitated. Patterns in mineralization will be observed in different parts of the aquifer, depending on gradients between surface and subsurface waters (e.g., Barnes and O'Neil 1969; Plummer et al. 2003; Kühn 2004). These

Table 1.20. Samples and measurements implied by Investigation Strategy 1.3B.

Samples identified to advance Investigation Strategy 1.3B:
• Samples from cross sections of altered zones. Key phases include Fe and Mn oxides, phyllosilicates, silica, sulfates, carbonates, and other salts. Samples should be selected with knowledge of their position within the flow path to track fluid chemistry change with system time evolution or distance.
Measurements identified to advance Investigation Strategy 1.3B:
• Determine all phases present in mineral assemblages in host rock and in groundwater-altered or -precipitated zones.
• Determine the crystal chemistry and valence of redox sensitive elements (Fe, Mn, Cr, S, etc.).
• Examine the petrologic relationships between primary and secondary minerals to determine the chemical reactions taking place in the groundwater system and the fluid chemistry.
• Evaluate flow volumes, fluxes, and water–rock ratios from the mineral assemblages and their relative timings of formation.
• Establish the relative timing of each mineral formation to understand the evolution of the groundwater system and reactive flow transport.

observations can be used to track the geochemical evolution of the fluid, including the potential production of microbial energy sources (e.g., H_2 gas) and/or water/rock ratio (e.g., McCollom and Bach 2009; Klein et al. 2013).

Table 1.20 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.3B and move toward understanding of a Martian subsurface groundwater systems.

<u>Investigation Strategy 1.3C:</u> Determine the source of fluids and abiotic or biotic reactions governing mineral precipitation.

Mineral phases and H, C, N, S, O, and metal isotopes can be used to understand the relative contributions from different fluid sources (atmospheric, groundwater, magmatic). This is routinely done on Earth by sampling systems from top to bottom through aquifer rocks because the isotopic signatures of the atmosphere are distinct from magmatic sources are distinct from host rocks (e.g., Genereux et al. 2009; Wiederhold 2015). Thus, investigation of multiple samples helps determine flow path. In terrestrial systems, particular isotopic signatures are often interpreted to be representative of abiotic versus biotic activity (e.g., S isotopes; Rye et al. 1981) despite isotopic behaviors that make such interpretations complicated (e.g., C isotopes in methane; Miller et al. 2016, 2017; Etiope 2017). Isotopic tools are being modified and applied to unravel the history of formation and alteration of meteorites (Leshin and Vicenzi 2006), C isotopes (Halevy et al. 2011), N isotopes (van Kooten et al. 2018), and in situ rocks from Gale Crater S isotopes (Franz et al. 2017). Correlating Martian isotopic signatures to abiotic versus biotic activity may be attempted but would be challenging (Etiope 2018). Similarly, observation of particular mineral phases may be indicative of the occurrence of specific temperature regimes and reaction mechanisms for mineral precipitation on Mars (e.g., Ehlmann et al. 2011b)

Table 1.21. Samples and measurements implied by Investigation Strategy 1.3C.

Samples identified to advance Investigation Strategy 1.3C:
• Samples suggested for IS 1.3A and 1.3B, but with an emphasis on sampling multiple positions in the inferred flow path through the host rocks and minerals deposited by multiple episodes of interaction.
Measurements identified to advance Investigation Strategy 1.3C:
• Measure H, C, S, O, and metal isotopes of mineral phases in the host rock and in groundwater-altered zones.
• Determine isotopic signatures from IS 1.3A as function of stratigraphic location and level to determine direction of water flow (top down versus bottom up).
• Measure atmospheric isotope values from coeval systems (e.g., glasses, quenched lavas).

Table 1.21 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.3C and move toward understanding of a Martian subsurface groundwater systems.

<u>Investigation Strategy 1.3D:</u> Determine the absolute time evolution of the groundwater system and chemical reactions.

We would like to know both the relative and absolute timing of when groundwater was present. Petrological relationships (overgrowths, crosscutting relationships) can used to determine the time at which groundwaters were present and interacting with the rocks by time-ordering the formation and dissolution of phases. This will also lead to understanding changes in groundwater properties due to changing sources or fluid evolution. This has been done on Mars in a relative sense at the *Opportunity* (McLennan et al. 2005; Tosca et al. 2005) and *Curiosity* (Siebach et al. 2014) landing sites. The measurements are similar to those in Investigation Strategies 1.2B and 1.2C, but with emphasis on in situ data to understand the number of episodes of groundwater interactions to select the best samples to establish timing.

Table 1.22. Samples and measurements implied by Investigation Strategy 1.3D.

Samples identified to advance Investigation Strategy 1.3D:

- Samples suggested for IS 1.3C.

Measurements identified to advance Investigation Strategy 1.3D:

- Identify zones of mineral precipitation and dissolution.
- Determine the sequence of chemical events affecting the rock from petrology.
- Determine the stable isotopic values for all phases measured in IS 1.3A-C, sampling those from distinct episodes.
- Perform radiometric age dating of samples from the host rock and minerals precipitated during each episode.

Table 1.22 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.3D and move toward understanding of a Martian subsurface groundwater systems.

1.4 Sub-Objective 1.4: Understand Water/Rock/Atmosphere Interactions at the Martian Surface and How They Have Changed with Time

UNDERSTAND SURFACE WATER/ROCK/ ATMOSPHERE INTERACTIONS	
Why is this objective critical?	*A key input into interpreting the history of water on Mars; search for life.*
Which are the most important samples?	*A suite of rocks or soils/paleosols representative of the range of depth and weathering, from most altered to least altered/unaltered parent material; mineral deposits formed due to evaporation.*

1.4.1 Introduction and Current State of Knowledge

The category of subaerial environments includes all environments at the surface or in the near-surface not covered by a body of water, but where water is derived directly from precipitation, snow melt, ambient-temperature groundwater, or atmospheric water vapor via deliquescence, as described by Hays et al. (2017). This includes soils, wetlands, ephemeral ponds, cold springs, rock coatings and weathering rinds, glaciers, periglacial terrains, and snow packs. These environments are often co-located both on modern Earth and in the terrestrial rock record (Fig. 1.14). Subaerial alteration probably occurred primarily during the Noachian and Hesperian on Mars and probably contributed to many of the hydrous outcrops on the

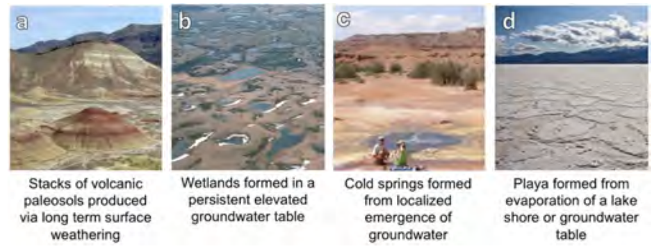

Fig. 1.14. Images of subaerial environments, which are linked by their common interactions with the atmosphere and water at the near surface. (a) Paleosol sequence formed on volcanic material, John Day Fossil Beds National Monument, Oregon. (b) Wetlands in a postglacial environment, Alberta, Canada. (c) Circumneutral cold spring near Green River, Utah (photo: S. Potter-McIntyre). (d) Playa environment in Death Valley, California.

surface (e.g., Bishop et al. 2008, 2018; Mustard et al. 2008; Murchie et al. 2009; Ehlmann and Edwards 2014) and thus investigating these materials on Mars will provide information about the aqueous geochemical environment and climate during their formation. These types of environments also represent potential habitable environments on early Mars. These environments are typically identified in the rock record by the presence of paleosol (lithified soil) profiles that can be topped by aqueously deposited sediments and precipitates from wetlands, ephemeral ponds, and springs. Thus, on Mars, these diverse environments are likely to be found in the rock record at the same landing site (Fig. 1.14).

Terrestrial soils, also termed the "Critical Zone" for their importance in hosting terrestrial life (Brantley et al. 2006), can preserve extensive evidence for habitable environments, aqueous conditions, and life. The processes that form a soil—transformation from one component to another, translocations or transport within the soil, additions and losses—all cause changes in the soil which are essential to understanding the chemistry and aqueous processes that support these habitable environments, and preserve potential signs of life. Where soils are seasonally or perennially saturated by surface runoff or groundwater, wetlands and similar shallow aqueous environments form and can preserve high abundances of organics due to their strongly reducing conditions. Soils are preserved in the geologic record as paleosols, and the composition and morphology of paleosols preserve evidence of past climate, aqueous conditions, and life (Retallack 2008). Examples of Mars analog paleosol sequences on Earth include the John Day Fossil Beds National Monument (e.g., Horgan et al. 2012) and the Painted Desert (McKeown et al. 2009; Noe Dobrea et al. 2009; Perrin et al. 2018). At these sites, horizons of diverse clay minerals, iron oxides, and sulfates document changes in climate and redox conditions (Fig. 1.15). On Mars,

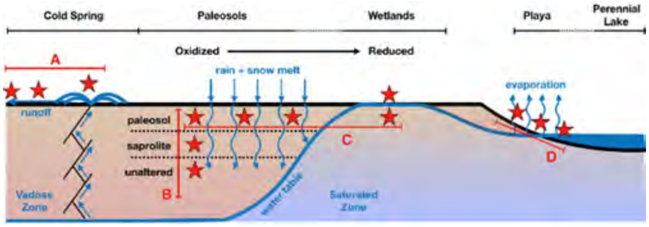

Fig. 1.15. Possible relationships between spring deposits, soil horizons, and evaporite deposits. Stars indicate proposed sample locations. Sample suite (A) is of spring precipitate deposits at increasing distance from spring source along fluvial channels. Sample suite (B) is paleosol horizons at increasing depths from the paleosurface, from highly altered to unweathered parent material. Sample suite (C) are paleosols at variable redox states, including reduced wetland deposits. Sample suite (D) is playa evaporite deposits at increasing distance inward from highest lake level. Proposed samples not shown here include rock coatings and rinds.

Noachian weathering profiles have been identified across the southern highlands (Carter et al. 2015), and possible paleosol sequences are present in Arabia Terra, in particular Mawrth Vallis (e.g., Bishop et al. 2008, 2018; Horgan et al. 2012).

More recent alteration on Mars has possibly led to less pervasive near-surface alteration. Potential near-surface activity includes mobility of Cl salts related to Recurring Slope Linea (RSL) (Ojha et al. 2015), long-term surface weathering (Amundson et al. 2008), and melting of H_2O ice near the *Phoenix* landing site (Smith et al. 2009) and in mid-latitude cliff sites (Dundas et al. 2018). Weak pedogenic alteration was also observed in Gusev Crater (Arvidson et al. 2010). Surface environments can also be recorded in weathering rinds and rock coatings (e.g., Sak et al. 2004; Hausrath et al. 2008a, 2008b; Navarre-Sitchler et al. 2009, 2011; Bishop et al. 2011; Dorn 2013; Adcock et al. 2018). Rock coatings and rinds have been observed with rovers and landers at the Martian surface (e.g., Hurowitz et al. 2006), and have been potentially identified from orbit (N. T. Bridges et al. 2001; Greeley et al. 1999; Haskin et al. 2005; Horgan and Bell 2012; Salvatore et al. 2013; Clark et al. 2016; Farrand et al. 2016). These more modern surface environments could still be targets for biosignature or extant life investigations, as even in desert environments, terrestrial microbes inhabit chemically active zones just below the surface (Fig. 1.16). Modern Mars-like soils on Earth include the Antarctic Dry Valleys, where despite the cold and dry surface conditions, near-surface changes in chemistry and mineralogy are attributed to an active zone in these sediments a few cm below the surface (e.g., Gibson et al. 1983; Burton et al. 2018). Thus, characterizing the near-surface profiles of Martian samples could provide information about chemical alteration occurring in these sites despite a harsh surface environment. This could indicate near-surface water availability when the Martian climate was cold and dry.

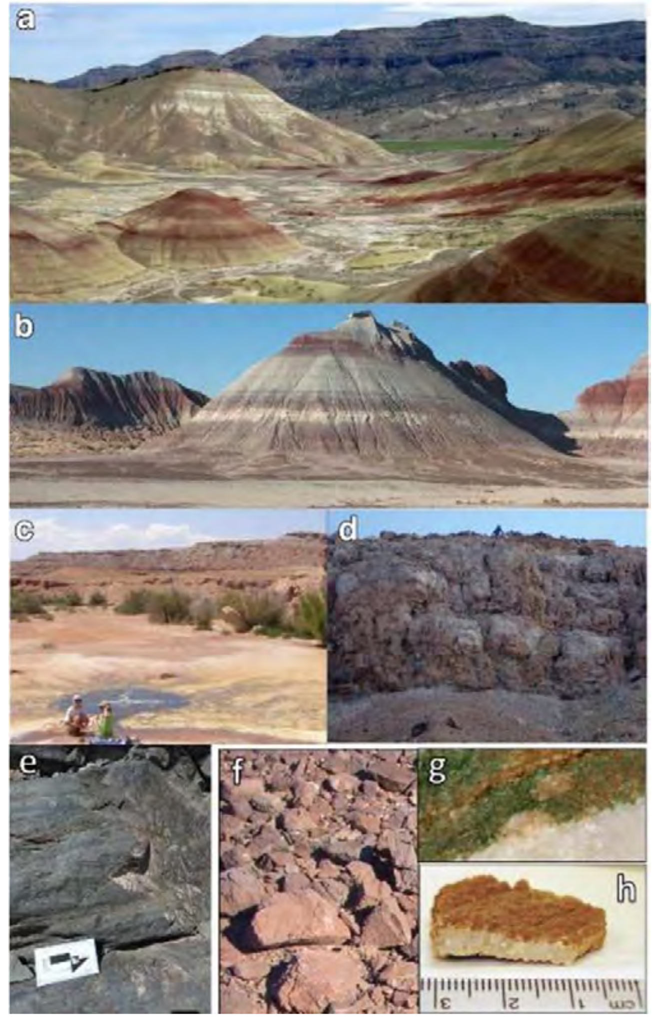

Fig. 1.16. Selected views of terrestrial subaerial environments. a) Paleosol sequence, John Day Fossil Beds National Monument, Oregon. b) Paleosol sequence, Painted Desert outcrop, Petrified Forest National Park, Arizona. (c) Modern circumneutral cold spring supporting surface microbial communities near Green River, Utah, compared to (d) outcrop of Jurassic cold spring deposits in the Brushy Basin Member of the Morrison Formation, Colorado (modified from Potter-McIntyre et al. 2016). (e) Glacially precipitated silica rock coatings (regelation films) on North Sister volcano, Oregon, compared to (f–h) red iron (oxyhydr)oxide coatings on carbonate rocks from the Mojave desert (modified from Bishop et al. 2011).

Ephemeral ponds are typically precipitation-sourced shallow lakes that can evolve into brines and can become acidic or alkaline. These ponds typically produce Cl-salt, sulfate, or carbonate deposits, and could support either phototrophic surface communities or chemotrophic communities where chemical gradients are present. The possibility of acid waters on Mars was first proposed by Clark and Baird (1979) and confirmed in situ by the *Opportunity* rover in Meridiani (Squyres et al. 2004). Sulfate salts are common across the Martian surface, and localized sulfates in locations like Mawrth Vallis have been interpreted as evidence of brines in ponds or wetlands (Horgan et al. 2015; Bishop et al. 2018). More neutral to alkaline evaporite deposits have also been identified on Mars, including localized Cl-salt deposits that are distributed throughout the southern highlands (Osterloo et al. 2008). Terrestrial analogs for brines on Mars include the shallow, acid brine lakes in Western Australia that are rich in microbial life, have variable pH, and have unique mineral assemblages (clays, FeOx, sulfates, and Cl salts) that could be representative of ancient habitable environments on Mars (Benison and LaClair 2003; Benison and Bowen 2006; Benison et al. 2007).

Cold springs are subaerial environments where ambient-temperature water emerges from the subsurface onto the surface. Typically, the flow path for the water is along faults or fractures, and changing chemical conditions as the water emerges onto the surface lead to the precipitation of mineral deposits. Spring-deposited tufas (calcium carbonates), clays, and iron (oxyhydr) oxide deposits can be preserved over geologic time, along with textural, mineralogical, and chemical biosignatures. Changing water chemistry can support chemotrophic communities, and flowing surface water can help to support phototrophs. In general, the significant energy availability produces abundant biomass in cold springs; therefore, biosignatures are highly concentrated in cold springs. Examples of these cold streams include ferrihydrite precipitating from runoff on tufas in Iceland (Bishop and Murad 2002) and carbonates precipitating at Mammoth Spring at Yellowstone (Bishop et al. 2004). These systems would require environments supporting at least short-term liquid water on the surface of Mars. Deeper groundwater systems could provide a source for these springs and seeps on the surface.

1.4.2 Key Open Questions for Sub-Objective 1.4

What was the nature of the early climate and atmosphere of Mars? The nature of the early climate of Mars is highly debated, and models range from cold and dry to warm and wet. Subaerial environments provide a record of direct atmosphere–surface interactions in the depth, geochemistry, and mineralogy of soils (e.g., Sheldon and Tabor 2009), and thus are a critical target for resolving the nature of the ancient Noachian climate (Carter et al. 2015; Horgan et al. 2017).

How habitable/inhabited was the ancient surface of Mars? Subaerial environments on Earth support a variety of microbial metabolic pathways both at the surface and in the near-surface environment, in part due to the complex chemistry created by surface–atmosphere interface, which creates redox gradients due to downward flow of precipitation in soils, groundwater fluctuations, evaporation and concentration of brines, subglacial fluid flow, and spring emergence. Thus, these environments can support chemotrophic and phototrophic microbial communities that may be present as microbial mats, endoliths, or other microbial communities of varying complexity and density. The terrestrial record shows that subaerial environments can preserve biosignatures from both surface (e.g., microbial mats; Watanabe et al. 2004) and subsurface life (e.g., concentrated organics; Gay and Grandstaff 1980).

How habitable is the modern surface of Mars, and what is the present-day surface/atmosphere water cycle? Despite the cold and dry surface conditions, the near-surface environment on Mars may have provided (or even still provide) in some locations access to liquid water, chemical alteration, and potentially habitable conditions. A full understanding of the present-day surface/atmosphere water cycle is still unknown to date. Modern soils integrate atmospheric processes over longer time spans than missions can sample (hundreds to millions of years). Characterization of modern soil and rock coating samples in the lab would enable a comprehensive understanding of near-surface present-day processes on Mars (Table 1.23).

1.4.3 Why Returned Sample Studies Are Important for Sub-Objective 1.4

Laboratory analysis of samples from this diverse suite of surface environments would allow detailed characterization of the composition of minerals produced in these environments. Mainly because fluids in most of these environments are either sourced from or directly interact with the atmosphere, the isotopic compositions of authigenic minerals provide direct links to past atmospheric conditions. Furthermore, these environments record long-term surface processes through deep weathering to form soil profiles, so characterization of subaerial Martian samples in the laboratory would include compositional analyses of

Table 1.23. Key open questions for Sub-Objective 1.4: Understanding water/rock/atmosphere interactions at the Martian surface.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.4
What was the nature of the early climate and atmosphere of Mars?
How habitable/inhabited was the ancient surface of Mars?
How habitable is the modern surface of Mars, and what is the present-day surface/atmosphere water cycle?

sampled horizons in order to document changes in the geochemical environment over time. The investigation of samples from this kind of environment in the lab would also optimize the chances of finding biosignatures and would help to characterize the present-day potential habitability of Mars.

1.4.4 Sample Investigation Strategies to Achieve Sub-Objective 1.4

Four investigation strategies and 12 sets of measurements have been proposed to unveil the change with time of the Martian surface water/atmosphere/rock interactions, characterize the past climate and geological changes and the potential of these environments to host and transport life and biosignatures as well as the redox states over time (Table 1.24). Below we detail the proposed Mars sample investigation strategies needed to interpret these aqueous environments and their potential biosignatures, listed in order of priority.

Investigation Strategy 1.4A*: *Investigate weathered materials such as soils, paleosols, weathering rinds, or rock coatings to investigate the duration and nature of past climates and both ancient and modern habitable surface environments.

Table 1.24. Summary of sample-related investigation strategies to understand a Martian water/rock/atmosphere interactions.

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.4		
1	**Geological environment(s)**	**Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.**
1.4	Subaerial	Understand water/rock/atmosphere interactions at the Martian surface and how they have changed with time.
IS 1.4A	Investigate weathered materials such as soils, paleosols, weathering rinds, or rock coatings to investigate the duration and nature of past climates and both ancient and modern habitable surface environments.	
IS 1.4B	Assess the history of surface water at the site, including the chemistry, source, and longevity of the waters, and their role in the formation of wetlands, ponds, and springs.	
IS 1.4C	Assess the aqueous and diagenetic history of the site, including the chemistry of past surface waters and groundwaters, how these water sources may have interacted, and how they have changed through time.	
IS 1.4D	Determine sediment provenance and transport history.	

Temperature on Mars likely plays a role in the relative dominance of physical and chemical weathering and is reflected in the mineralogy of soils and paleosols. For example, smectite clays formed in surface environments on Mars required warmer temperatures than poorly crystalline aluminosilicates formed in neighboring surface environments (Fairén et al. 2011; Bishop and Rampe 2016), thus indicating a change in climate (Bishop et al. 2018). Allophane and related poorly crystalline materials have been observed in cold terrestrial environments (e.g., Bishop et al. 2014; Scudder et al. 2017; Thorpe et al. 2017; Cuadros et al. 2018) rather than crystalline clays. Detailed analysis of the crystalline mineral and amorphous phase assemblages in weathering profiles could help to constrain the origin of these different minerals and their relationship to past environmental conditions (e.g., Gainey et al. 2017). Near-surface active zones in the Antarctic Dry Valleys are identified through changes from anhydrite to gypsum, from amorphous aluminosilicates to montmorillonite, and through elevated NaCl levels (Gibson et al. 1983; Englert et al. 2013; Bishop and Englert 2016). Identifying similar mineral/chemical transitions with depth in Martian samples could provide evidence of near-surface active zones on Mars in the ancient or recent past.

In addition, on Earth, stable isotopes and geochemical profiles are used to constrain paleoprecipitation and paleotemperature in paleosols, and similar calculations may be possible using Martian samples (e.g., Retallack et al. 1999; Sheldon and Tabor 2009). The thickness of soils and weathering rinds can be used to interpret the duration of weathering (Sak et al. 2004; Hausrath et al. 2008a, 2008b; Navarre-Sitchler et al. 2009, 2011; Adcock et al. 2018), and so ultimately these investigations would help to constrain the duration and degree of habitability of Martian surface and the landing site and on Mars more generally. Subaerial environments could have been widespread on Mars, so if these environments were habitable, then the Martian surface was probably largely habitable, habitats were well-connected, and Mars could have supported significantly more total biomass (e.g., Westall et al. 2015a). In addition, the composition and stable isotopes of minerals produced through alteration by meteoric water can be used to constrain atmospheric chemistry and atmospheric change through time (e.g., carbonates; Hu et al. 2015)—there is an important cross-link in the area with Objective 4 of this report. By comparing the composition of minerals generated from meteoric water sources versus those from groundwater sources, we could also constrain the composition and history of different volatile sources and sinks on Mars.

A critical component of this investigation is changes in mineralogy and chemistry with depth, which is a better indicator of past aqueous processes and climate than a single measurement or samples alone (e.g., Sheldon and Tabor 2009). In addition, chemical profiles can preserve potential biosignatures in highly leached and oxidized paleosol profiles, including laterites. Although these types of soils have poor organic preservation potential, they can preserve chemical biosignatures, including "bleached" Fe-poor upper horizons attributed to organic acids from surface microbial communities (Gutzmer and Beukes 1998; Neaman et al. 2005; Hausrath et al. 2011), phosphorus depletion in the upper portion of profiles that could indicate uptake by microorganisms (Horodyskyj et al. 2012), and potential impacts of biological Fe oxidation (Baumeister et al. 2015).

Table 1.25 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.4A and move toward understanding of water/rock/atmosphere interactions at the Martian surface.

Table 1.25. Samples and measurements implied by Investigation Strategy 1.4A.

Samples identified to advance Investigation Strategy 1.4A:

- A suite of rocks or soils/paleosols representative of the observed range of depth and weathering, from most altered to least altered/unaltered parent material.
- Mineral deposits (e.g., iron oxides, salts, carbonates) precipitated in chemical gradients (e.g., springs) or due to evaporation (e.g., ephemeral ponds), especially those with evidence for long-term buildup.
- Rocks with precipitated coatings and/or rinds.

Measurements identified to advance Investigation Strategy 1.4A:

- Measure variability in the mineralogy, chemistry (including identification and measurement of potential oxidants), mineral proportions and morphology of primary and secondary minerals and amorphous phases as a function of depth and/or degree of weathering, to constrain the duration of water interaction, water chemistry, water temperature, water residence time/drainage, and search for chemical trends that could be biosignatures.
- Analyze the chemistry and mineralogy of climate-sensitive minerals at nano-, micro-, and macro-scales.
- Measure the micro- and nanoscale morphology, thickness, and chemistry of rinds and coatings.
- Measure the stable isotope compositions of secondary minerals to constrain the composition and history of atmospheric and crustal volatile sources.
- Determine the radiometric ages of applicable secondary mineral phases (e.g., jarosite)

Investigation Strategy 1.4B: Assess the history of surface water at the site, including the chemistry, source, and longevity of the waters, and their role in the formation of wetlands, ponds, and springs.

Subaerial environments include those environments where water ponds at the surface in the form of wetlands (stagnant, reducing bodies of water at the intersection with the local groundwater table), ponds (surface accumulation of water), lake shorelines, and cold springs. Although soils tend to form a chemical record by alteration of pre-existing parent materials, these subaerial environments can also cause significant sediment accumulation and mineral precipitation at the surface.

Surface mineral precipitates include direct precipitates, evaporites, and coatings, and can preserve fluid inclusions, trapped organics, and surface textures that, along with chemistry and mineralogy, can help to untangle the history of water at the site. Precipitates are also critical for preserving biosignatures. Cold springs in particular can produce a diverse suite of mineral deposits (e.g., carbonates, clays, sulfates/salts, amorphous minerals), which enable multiple biosignature preservation mechanisms. Ostwald ripening (where large crystals form at the expense of smaller crystals, resulting in massive, anhedral crystal habits in Jurassic tufas) has been shown to preserve microbial body fossils and trace fossils in carbonates on geologic time scales (Potter-McIntyre et al. 2016). Iron-rich springs have also been shown to preserve lipid biomarkers (Parenteau et al. 2014). Evaporite deposits can preserve biosignatures in the form of filamentous structures and trapped organics in mineral crystals (e.g., Vreeland et al. 2000; Mormile et al. 2009). Redox changes in evaporates might represent a more direct link to changes in geochemical environment and potentially the presence of microbes (Benison and Bowen 2006). In any precipitate, examination of organic inclusions could provide information about the geochemical conditions at time of emplacement and potentially provide clues to any microbes associated with them.

Table 1.26 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.4B and move toward understanding of water/rock/atmosphere interactions at the Martian surface.

Investigation Strategy 1.4C: ***Assess the diagenetic history of the site, including the chemistry and redox state of past near-surface waters and groundwaters, how water sources may have interacted, and how they have changed through time.***

Many locations on Mars show evidence for interaction with both surface waters and groundwaters

Table 1.26. Samples and measurements implied by Investigation Strategy 1.4B.

Samples identified to advance Investigation Strategy 1.4B:

- Rocks formed under a variety of redox conditions, and especially those with evidence for sedimentation or mineral precipitation under reducing conditions.
- Mineral deposits (e.g., iron oxides, salts, carbonates) precipitated in chemical gradients (e.g., springs) or due to evaporation (e.g., ephemeral ponds), especially those with evidence for long-term buildup.
- Rocks with precipitated coatings or weathering rinds.

Measurements identified to advance Investigation Strategy 1.4B:

- Evaluate the chemical and isotopic composition, speciation, and abundance of organics, lipids, etc. in sedimentary and mineral precipitate deposits, in particular those with reduced Fe/S minerals and mineral precipitates, in order to determine whether or not organics may be biotic in origin.
- Analyze the micro- and nanoscale morphology of mineral precipitates to search for textural biosignatures.
- Determine the composition and isotopic signatures of fluid inclusions and associated dissolved gases.

during early alteration (early diagenesis). Downward leaching of surface waters into the near-surface produces paleosols. Where this process occurs well above the water table, an oxidized and well-leached paleosol is produced, but as the water table nears the surface, the paleosol can become seasonally or perennially saturated, to the point of becoming a wetland (Fig. 1.15). Saturated soils and wetlands rapidly become reducing, and form less leached mineral phases. This process can create strong lateral, vertical, and temporal redox gradients that strongly affect biosignature preservation, enable chemolithic metabolisms in microbes, and alter the chemistry of the alteration fluids and their precipitated minerals. Both well-leached (e.g., Carter et al. 2015) and reducing (e.g., Bishop et al. 2013; Farrand et al. 2014; Horgan et al. 2015) paleosol profiles have been tentatively identified on Mars, and these paleosols could preserve key chemical and mineralogical information about the surface and groundwaters that formed them, and the interactions of these water sources.

This investigation is also critical for characterizing the organic preservation potential of soils and paleosols. Organics are most easily concentrated and preserved when they are deposited in a reducing surface or near-surface environment. Paleosols most commonly preserve organics when they are associated with seasonal or permanent waterlogging (e.g., wetlands), which in the more modern terrestrial environment can lead to the formation of lignites, tonsteins, and seatearths (Spears 2012). However, paleosols associated with surface reducing conditions (e.g., ponds) have also been shown to preserve organic carbon for billions of years both at the surface and at depth at detectable levels (0.01–0.36 wt%) from microbial communities (Gay and Grandstaff 1980; Rye and Holland 2000; Watanabe et al. 2000, 2004). Redox state appears to be the most critical indicator of this kind of preservation, as nearby contemporaneous oxidized and heavily leached profiles do not contain organics (Gay and Grandstaff 1980). Studies of more recent paleosol sequences have shown concentrations of organics can also occur in association with sulfates (Noe Dobrea et al. 2016).

In addition, the advanced age of many Martian geologic units also allows for significant alteration post-burial (late diagenesis)—there is an important connection in this area to Sub-Objective 1.3 of this report. This has been shown at the rover scale based on the presence of fractures filled with diverse precipitated minerals and chemistries (e.g., Siebach and Grotzinger 2014), including ubiquitous Ca-sulfates (e.g., Rapin et al. 2016), some with enriched Fe (L'Haridon et al. 2018); silica halos (Frydenvang et al. 2017); and Mn oxides (Lanza et al. 2016). At the orbital scale, diagenesis is inferred based on the presence of resistant linear ridges, sometimes with alteration halos, interpreted as fractures through which diagenetic fluids flowed (e.g., Loizeau et al. 2015; Bramble et al. 2017). Comparison of late diagenetic features and those from surface deposition or early diagenesis would constrain the evolution of fluid compositions on Mars over time (e.g., Hausrath et al. 2018), and as late diagenesis can destroy previously preserved organics, would help to inform analyses of biosignature preservation potential.

In all these aqueous near-surface or surface environments, the solution chemistry of past aqueous environments is relevant to critical aspects of potential habitability and biosignature preservation. Samples that preserve evidence of that chemistry are therefore a high priority for sample selection. Important characteristics of habitability that can be preserved in aqueously altered samples include the nutrients and redox gradients present, and characteristics of liquid water such as temperature, pH, and salinity. Similarly, solution chemistry is critical to biosignature preservation, and solution chemistries high in Fe, phosphate, silica, and carbonate have all preserved different types of biosignatures on Earth. Reducing conditions are important for preserving organic compounds.

Table 1.27 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.4C and move toward understanding of water/rock/atmosphere interactions at the Martian surface.

Table 1.27. Samples and measurements implied by Investigation Strategy 1.4C.

Samples identified to advance Investigation Strategy 1.4C:

- A suite of rocks or soils/paleosols representative of the observed range of depth and weathering, from most-altered to least-altered/unaltered parent material.
- Rocks formed under a variety of redox conditions, and especially those with evidence for sedimentation or mineral precipitation under reducing conditions.
- Mineral deposits (e.g., iron oxides, salts, carbonates) precipitated in chemical gradients (e.g., springs) or due to evaporation (e.g., ephemeral ponds), especially those with evidence for long-term buildup.
- Rocks with precipitated coatings or rinds.
- Rocks with diagenetic features (e.g., fracture-filling mineral precipitates).

Measurements identified to advance Investigation Strategy 1.4C:

- Measure variability in the mineralogy, chemistry (including identification and measurement of potential oxidants), mineral proportions, and morphology of primary and secondary minerals and amorphous phases as a function of depth and/or degree of weathering, to constrain the duration of water interaction, water chemistry, water temperature, water residence time/drainage, and search for chemical trends that could be biosignatures.
- Analyze the chemistry and mineralogy of climate-sensitive minerals at nano-, micro-, and macroscales.
- Measure the stable isotope compositions of secondary minerals to constrain the composition and history of atmospheric and crustal volatile sources.
- Measure radiometric ages of primary and secondary minerals with permissible mineralogy to determine ages of formation and diagenetic events.
- Determine the oxidation states of minerals to infer position of soils/paleosols relative to the paleo-water table, and exposure to reducing and oxidizing components (including photochemical).

Investigation Strategy 1.4D: Determine sediment provenance and transport history.

Where they form in sedimentary units, paleosol samples serve a dual purpose as both records of chemical weathering and physical deposition of sediments—there is an important connection in this area to Sub-Objective 1.1 of this report. One of the biggest ongoing changes in our view of Mars is the recognition of the dominance of sedimentary processes over coherent bedrock (e.g., lava) on the surface. Recent investigations of the ancient southern highlands using morphology, mineralogy, thermal properties, and superposition relationships have shown that friable, layered rocks are much more common than previously thought (Edgett 2016; Rogers et al. 2017), and when combined with known regional sedimentary layered deposits like Arabia Terra, Meridiani Planum, etc. (e.g., Malin and Edgett 2001; Lewis et al. 2008; Kerber et al. 2012), these observations suggest that Mars has had extremely active sedimentary cycle. Indeed, many weathering sequences possibly indicative of paleosols are associated with sedimentary units (Noe Dobrea et al. 2010; Carter et al. 2015). However, the origins of the sediments themselves are not well understood. Detailed compositional and micromorphological analysis of returned sedimentary rock and modern sediment samples would help to constrain the origin and transport history of local sediments at the sampling location and more broadly on Mars.

Table 1.28 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.4D and move toward understanding of water/rock/atmosphere interactions at the Martian surface.

Table 1.28. Samples and measurements implied by Investigation Strategy 1.4D.

Samples identified to advance Investigation Strategy 1.4D:

- A suite of rocks or soils/paleosols representative of the observed range of depth and weathering, from most altered to least altered/unaltered parent material.

Measurements identified to advance Investigation Strategy 1.4D:

- Analyze the microscale physical, chemical, and mineralogical properties of sediments to constrain transport history and determine the relative importance of physical and chemical weathering.
- Measure cosmogenic nuclides to determine exposure age and erosion rate.

1.5 Sub-Objective 1.5: Understand the Essential Attributes of a Martian Igneous System

UNDERSTAND A MARTIAN IGNEOUS SYSTEM	
Why is this objective critical?	*Key input into the mechanisms for formation of igneous rocks and the evolution of Mars on a planetary scale*
Which are the most important samples?	*A suite of igneous rocks as diverse in composition and texture as possible. Both in situ (outcrop) and ex situ (transported) sampling opportunities should be considered in order to maximize diversity.*

1.5.1 Introduction and Current State of Knowledge

Igneous rocks record the thermochemical evolution of a planet from its core to its atmosphere, and each rock type provides insights into the complexity of that history. In particular, basaltic rocks are a direct window into the planetary interior and provide constraints on the starting conditions for the isotopic composition of the atmosphere. Mars is fundamentally a basaltic planet: in situ compositional and mineralogical measurements on the Martian surface, combined with analyses of Martian meteorites, indicate that most igneous rocks are lavas and volcaniclastic rocks of basaltic composition and ultramafic cumulates from basaltic magmas (McSween 2015; Filiberto 2017). However, alkaline and feldspathic igneous rocks have also been identified both in situ (e.g., Sautter et al. 2015), from orbit (e.g., Christensen et al. 2005; Rogers and Nekvasil 2015), and in the meteorite collection (Santos et al. 2015; Nekvasil et al. 2007).

1.5.2 Key Open Questions for Sub-Objective 1.5

A key outcome of the comparison between the igneous rocks in the Martian meteorite suite and those analyzed on the surface of Mars (e.g., by *Pathfinder*, MER and *Curiosity* rovers, or using orbital spectroscopy) is that the Martian meteorites differ in elemental composition, age, isotopic composition, and inferred mantle source characteristics (Fig. 1.17) and are thus not representative of the crust of Mars nor do they represent the isotopic compositions of the present-day atmosphere (e.g., McSween et al. 2009; Filiberto et al. 2010a; Stolper et al. 2013; Villanueva et al. 2015; Ehlmann et al. 2016).

The dichotomy between the Martian meteorites and the igneous rocks at the surface of Mars can be partially reconciled by our understanding of the impact-

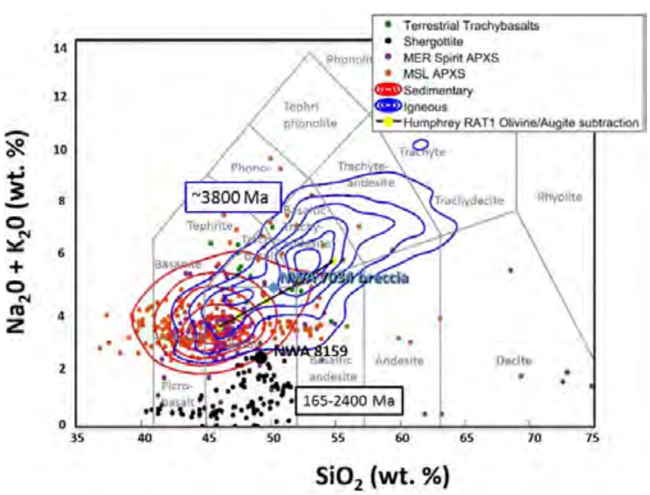

Fig. 1.17. TAS plot comparing sedimentary and igneous rocks from MSL ChemCam and MER APXS data, with the compositions of Martian meteorites. NWA 7034 is a breccia more representative of the Martian crust. NWA 8159 is a newly recognized, augite-rich type that is 2400 Ma (Herd et al. 2017). Figure after Edwards et al. (2017) (Table 1.29).

Table 1.29. Key open questions for Sub-Objective 1.5: Understanding Martian igneous systems.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.5
Is the mantle of Mars as inferred from the parent magmas of shergottite meteorites applicable to all of Mars?
What is the diversity of igneous rock compositions? Have they changed over time?
What did the mantle of Mars look like > 3.5 Ga? Was metasomatism involved?

driven mechanism by which the meteorites are delivered from Mars to Earth (Head et al. 2002) and the bias that mechanism imparts toward more competent—i.e., younger, igneous—samples (Jones 1989; Warren 1994; Head et al. 2002; Walton et al. 2008). The shergottites, which are basaltic igneous rocks that crystallized as decameter-scale flows or shallow sills, and which have undergone crystal fractionation and accumulation to varying degrees from starting mafic melts, are mostly late Amazonian in age (175–600 Ma); nevertheless, these rocks apparently tap mantle sources of varying geochemical characters—as elucidated by rare earth element (REE) patterns and radiogenic isotopic compositions—that were established during the very early stages of differentiation of the Martian mantle, by ~4500 Ma, probably through the crystallization of a magma ocean (e.g., Symes et al. 2008; Borg et al. 2016). The implication of this discovery is twofold: first, that the mantle of Mars has remained largely unmixed over most of its history, at least in the regions sampled by the shergottites (consistent with the lack of plate tectonic activity and the manifestation of convection via mantle plumes); second, that the mantle sources represented by the igneous rocks investigated at the surface of Mars (e.g., those investigated by *Spirit* and *Curiosity* rovers, which have estimated ages of ~3800 Ma) are distinct from those mantle sources represented by the Martian meteorites. How the mantle inferred from the meteorites relates to the mantle inferred from the igneous rocks at the surface of Mars is a fundamental question in the geologic evolution of Mars (e.g., McCoy et al. 2011). Whether magma ocean crystallization is the default first-stage of terrestrial planet formation is an open and fundamental question in planetary science and affects not only the lithosphere of a planet but also the starting conditions for the atmosphere. Both of these questions can be addressed through return of igneous samples from Mars.

1.5.3 Why Returned Sample Studies Are Important for Sub-Objective 1.5

Understanding the petrogenesis of igneous rocks sampled from well-documented locations within an

Fig. 1.18. For igneous rocks, the lithologic, textural, and chemical diversity of the sample collection is far more important than collecting only rocks with known outcrop-scale context. There are multiple geological processes that could transport diverse rocks to places where the rover could sample them. Igneous sampling strategies need to encompass both in situ (in outcrop) and ex situ (transported) options. Image notes: In situ: Hawai'i; Ex situ: Upper left: Low Ridge, Gusev (NASA/JPL-Caltech/Cornell/NMMNH); upper right: Gale Crater (NASA/JPL-Caltech/MSSS) lower left and right: Generic images from the web.

igneous terrane would provide novel insights into the physical properties of Martian magmas; the compositions of their mantle sources; the conditions of magma genesis; the timing, style, and duration of igneous activity; and the character and isotopic composition of volcanic emissions that would have been contributed to the Martian atmosphere at the time of eruption.

As these diverse rock types can be related to different geodynamic settings, they provide important constraints on the geologic history of Mars. The geochemical composition of magmatic rocks is also required for experimental petrology studies that constrain the mantle composition, the conditions of melting, and subsequent magmatic evolution, as has been done previously for both Martian meteorites and igneous rocks from Gusev and Gale (e.g., Filiberto et al. 2010b; Rapp et al. 2013).

Igneous rocks can probably provide a more definitive chronology than any other rock samples from Mars. With only one exception, the currently available Martian meteorites are all igneous rocks (e.g., McSween 2015; McCubbin et al. 2016a). However, they constitute a biased sampling of the igneous rocks on Mars in terms of both geochemistry and age, their geologic contexts (sampling sites) are unknown, and they have been variably affected by shock metamorphism and terrestrial weathering (McLennan et al. 2012). Nevertheless, from them we can conclude that Amazonian magmatism has been reasonably well sampled. From these limitations, the prioritized list of most desirable igneous targets for sample return can be derived: Noachian and/or Hesperian probable age; relatively unaffected by shock or weathering; basaltic rocks likely representative of their parent magmas; igneous rocks that are more evolved (silicic and/or alkaline); and lavas that contain mantle xenoliths.

1.5.4 Sample Investigation Strategies to Achieve Sub-Objective 1.5

The systematic exploration of an igneous terrane—for example, extrusive flows emanating from a vent—would involve the mapping and sampling of a range of igneous rock compositions. Sampling would likely need to occur over a wide area, given the sizes of igneous terranes on Mars (e.g., the Tharsis Montes, Hesperia Planum). One risk of this approach is that members of the suite of samples might not be meaningfully different from each other (e.g., similar ages, compositions, and textures), providing only a "snapshot" of igneous activity at one point in Mars's history and in one location.

There are two approaches to the exploration of igneous rocks on Mars: maximize the compositional diversity by targeting loose boulders (e.g., as was done for igneous rocks at Gusev Crater by the MER *Spirit* rover), and find igneous rocks still in place (i.e., in outcrop). While these two approaches may seem to be at odds with each other, the prioritization of the approach depends on the objective. Reconstructing the history of Mars as a planet, elucidating those processes that have affected the origin and modification of the crust, mantle, and core (Objective 5) is best done with a diversity of igneous rock types for which knowledge of the source outcrop is not necessary. However, determining the evolutionary timeline of Mars, including calibrating the crater chronology time scale (Objective 3), would potentially involve locating an igneous rock which belongs to a previously mapped unit with a known crater retention age. The latter approach is also necessary to provide radiometric age constraints on the deposition of interleaved sedimentary rocks included in the returned sample suite, and therefore context for the potentially life-hosting system being sampled (Objective 2).

As evidenced by previous rover missions (e.g., *Pathfinder*, *Spirit*, *Opportunity*, *Curiosity*), any landing site is likely to provide access to igneous samples as cobble- to boulder-sized rocks which have been removed from their original outcrops (transported by some process)—included in this category would be boulders on the surface ("float" or talus), within a streambed, or as clasts within conglomerate (Fig. 1.18). While samples from in situ rocks are best (whether in the outcrop or proximal to it) for certain investigations

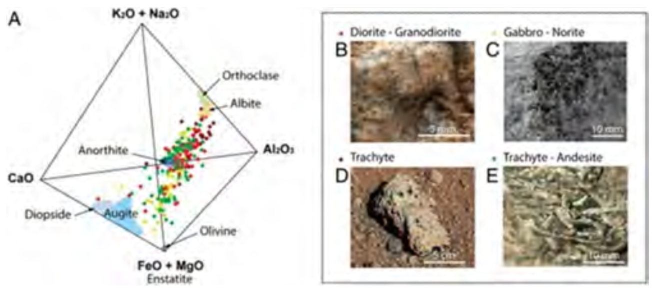

Fig. 1.19. The four main types of igneous rocks found around Bradbury landing site (MSL) (Sautter et al. 2016).

(e.g., placing age constraints on the Mars time scale), these ex situ samples of opportunity would likely provide the compositional diversity required to constrain the time-resolved geodynamical evolution of Mars (e.g., Fig. 1.19); any returned samples of igneous rock would be used to modify and expand existing models for the thermochemical evolution of Mars that were developed using data from Martian meteorites and data returned from Martian rover and orbital missions.

The following Investigation Strategy and five sets of measurements (Table 1.30) will enable the optimization of a suite of returned igneous samples from a given landing site, whether the samples are from rocks in place (in outcrop) or not (transported). Collecting samples of each rock type at a given site is needed as a baseline to characterize the geology at that site. If igneous petrologic diversity exists at a site, or even within a specific sample (e.g., clasts within a breccia or conglomerate, xenoliths within an extrusive lava), examining the diversity from a geochemical and petrologic standpoint can provide important insights into the geologic processes that have operated at that site. Geochemical studies can be used to determine whether all the rocks are petrogenetically related and what processes relate them to each other, including magmatic differentiation and secondary alteration. Alternatively, if geochemical studies indicate that rocks are not related at a specific site, it would indicate that the site hosts samples that are sourced from a wide catchment (e.g., through transport via impact or fluvial processes), and hence the igneous diversity can provide constraints on larger scale global Martian geochemical processes.

Table 1.30. Summary of sample-related investigation strategies to understand a Martian igneous system.

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.5		
1	**Geological environment(s)**	**Interpret the primary geologic processes and history that formed the Martian geologic record, with an emphasis on the role of water.**
1.5	Igneous terrane	Determine the petrogenesis of Martian igneous rocks in time and space.
IS 1.5A	Determine the compositional and textural diversity of igneous rocks and the time-resolved geological processes which relate them to each other and to Martian meteorites.	

Investigation Strategy 1.5A*: *Determine the compositional and textural diversity of igneous rocks and the time-resolved geological processes which relate them to each other and to Martian meteorites.

Geochemical studies of igneous samples on Mars when coupled with studies of radiometric dating will help to identify any important correlations between bulk rock geochemistry and age. Broad changes in the geochemistry of magmatic liquids over time are expected as a planet evolves and cools. Moreover, if temporal changes in geochemistry are observed, they would provide important constraints on the thermochemical evolution of the Martian mantle (e.g., potential mantle temperature, Fe/Si ratio, and volatile contents; Baratoux et al. 2011; Filiberto 2017). In fact, temporal correlations between geochemical features in Martian rocks have already been suggested: alkaline rocks appear to be common in older terranes on Mars, and tholeiitic rocks in younger terranes (McSween 2015; see also Fig. 1.17). Currently, however, this hypothesis remains to be tested, and precisely measuring trace element abundances and isotope ratios can only be done in laboratories on Earth. Additionally, the oldest volcanic rocks at the surface of Mars appear to have equilibrated at much higher oxygen fugacity than more recent episodes of volcanism (Herd 2003; Schmidt et al. 2013; Tuff et al. 2013). A suite of igneous rocks with ages not represented among the Martian meteorites would enable the determination of whether systematic variations in mantle source compositions and melting conditions have occurred over time (Filiberto et al. 2010b; Baratoux et al. 2011; Grott et al. 2013; McSween 2015; Filiberto 2017).

Table 1.31 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 1.5A and move toward understanding of Martian igneous systems.

2 OBJECTIVE 2: ASSESS AND INTERPRET THE POTENTIAL BIOLOGICAL HISTORY OF MARS, INCLUDING ASSAYING RETURNED SAMPLES FOR THE EVIDENCE OF LIFE

The process of carrying out a scientific search for life on Mars involves a progressive narrowing of the

Table 1.31. Samples and measurements implied by Investigation Strategy 1.5A.

Samples identified to advance Investigation Strategy 1.5A:

- A suite of igneous rocks as diverse in composition and texture as possible, both in situ (outcrop) and ex situ (transported).

Measurements identified to advance Investigation Strategy 1.5A:

- Measure variability in the mineralogy, texture, mineral proportions, and mineral chemistry (major, minor and trace element), and bulk compositions (major, minor, and trace element, and radiogenic isotopes) of igneous rocks in order to classify them relative to other igneous rocks from Mars, and determine whether they represent primary mantle melts or melts affected by interaction with other mantle or crustal sources or components.
- Measure the compositions of any volatile-bearing minerals or melt inclusions, and the redox states of multivalent elements, in order to determine the conditions of magma genesis and crystallization (e.g., T, P, X, fO_2) for each silicate melt, and to elucidate any changes in conditions during crystallization (e.g., in oxygen fugacity and/or volatile content).
- Quantify the textures of igneous samples through crystal size distribution analysis and mineral mapping techniques, in order to determine their setting (e.g., intrusive or extrusive) and the conditions during magma ascent, emplacement, and solidification.
- Measure radiometric ages (e.g., U-Pb, Ar-Ar, Sm-Nd, Lu-Hf, Rb-Sr) of each igneous rock from as many systems as feasible in order to obtain crystallization ages.
- Measure stable isotopic compositions (e.g., O, S, Fe, Mg) of minerals and bulk rock samples in order to quantify primary igneous and secondary (e.g., alteration or other modification) processes.

search space, culminating in definitive yes-no tests for the existence of past or present life in returned samples. The search process has three general components (see Fig. 2.1):

- Using orbital data, select geological terrain that reflects high potential for habitability, and high potential for the preservation of the evidence for both habitability and potential habitation. As discussed for Objective 1, Mars hosted a diverse array of ancient environments that vary widely in the type, abundance, and quality of biosignature evidence they could retain. Among the possibilities, the science community has established a clear set of environmental priorities which define the four target environments of Objective 1.
- From the Martian surface, use detailed geology and geochemistry investigations to narrow the spatial focus to sub-environments, and identify more localized priorities related to the potential for habitability, preservation, and habitation. These interpretations would be revisited later using the far more detailed investigations that are possible using returned samples.
- Select samples for two purposes (1) to refine understandings of the potential of the sub-environments, and (2) to test for the evidence of life. To achieve these purposes, two general categories of samples should be sought: samples that are typical (i.e., representative of significant volumes of rock on Mars), and samples that are anomalous (i.e., unusual texture, mineralogy, setting, etc.). Since we do not know how evidence for Martian life would be preserved in the geological record (if indeed it exists at all), we do not know exactly what we are looking for—this principle of collecting both representative and anomalous samples is very important.

There is therefore a critical connection between Objectives 1 and 2, as we have defined them. Efforts at life detection must be informed by assessments of (1) the nature and extent of habitability for a given environment, i.e., what conditions and processes supported or challenged life and over what time scales, (2) how might such environments have influenced the attributes of any biosignatures and also created nonbiological "mimics" that would challenge their definitive identification, and (3) the conditions and processes that enhanced preservation or degradation of biosignatures. In order for MSR to be judged by history to be a success, it needs to either find Martian life, or to significantly narrow the search space for future exploration activity.

Finding 5: An aspect of the search for evidence of life is that we do not know in advance how evidence for Martian life would be preserved in the geologic record. In order for the returned samples to be most useful for both understanding geologic processes (Objective 1) and the search for life (Objective 2), the sample collection should contain BOTH typical and unusual samples from the rock units explored. This consideration should be incorporated into sample selection and the design of the suites

In describing Objective 2, we felt that the logic of the problem required that we break it down into sub-objectives (Table 2.1). However, unlike the sub-objectives of Objective 1, we expect that *all* of these would be achieved with returned samples. Objective 1 (previous chapter) addresses environmental habitability and some aspects of preservation—these are key inputs into the life question. Sub-Objective 2.1 acknowledges the central importance that carbon holds for life, both

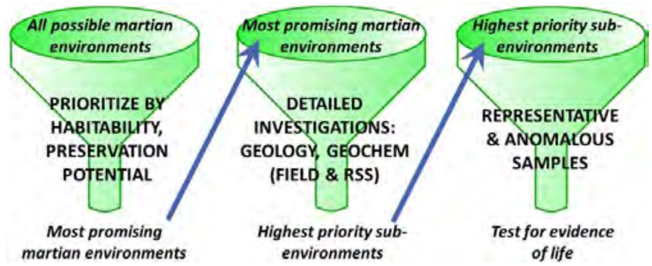

Fig. 2.1. The search for life on Mars involves a progressive narrowing of the search space, making use of orbital data sets, rover-based data sets, and returned sample data sets. Since we do not know how evidence for Martian life might be preserved in the Martian geologic record, it is important that the returned collection include both representative and anomalous samples.

Table 2.1. Division of Objective 2 into sub-objectives.

Objective 2	Life	Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life
Complete **ALL** of the following sub-objectives.		
Sub-Obj. 2.1	Carbon chemistry	Assess and characterize carbon, including possible organic and prebiotic chemistry
Sub-Obj. 2.2	Biosignatures —ancient	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures
Sub-Obj. 2.3	Biosignatures —modern	Assess the possibility that any life forms detected are still alive, or were recently alive

by shaping planetary environments and by creating the "backbones" of biological molecules. Sub-Objective 2.1 addresses important carbon sources, planetary processes, environmental contexts and the abiotic mimics of biology, that is, the nonbiological "noise." Finding evidence of either past or extant life on Mars would be a watershed event. However, significant differences exist in the strategies, technologies, target environments, and forms of evidence that would be most appropriate in searching for ancient versus extant life. Sub-Objective 2.2 addresses the variety of substances, structures and patterns that constitute the known array of ancient biosignatures of past life. These features also might constitute evidence of extant life if they are found in geologically recent deposits. Sub-Objective 2.3 is complementary to 2.2, in that it addresses additional biosignatures that could be sought as evidence of extant life. Thus, in certain respects, the analytic methodologies overlap between Sub-Objectives 2.2 and 2.3.

2.1 Sub-Objective 2.1: Assess and Characterize Carbon, Including Possible Organic and Prebiotic Chemistry

ASSESS AND CHARACTERIZE CARBON	
Why is this objective critical?	*Understanding the Martian carbon cycle in as much detail as possible is essential to understanding prebiotic chemistry, habitability, the possibility of habitation, and the preservation of the evidence of all of the above.*
Which are the most important samples?	*All of the samples collected as part of Objective 1 are of interest.*

2.1.1 Introduction and Current State of Knowledge

Evidence of habitability of Mars may be forthcoming by returning samples to Earth (McLennan et al. 2012). Clear objectives and associated choices of samples are essential to maximize the opportunities presented by returned samples. In the context of the solar system, the relative similarity of Earth and Mars generates an expectation of similar biochemistries for the two planets. We can confidently predict that any biochemical scaffolding on Mars would be based on carbon and any biochemical solvent would be based on water. To expect otherwise would require planetary conditions and chemistries (Taylor 2011) that differ dramatically from those of either Earth or Mars. Reduced carbon is therefore a beacon for the potential discovery of evidence of life or prebiotic chemistry in a sample (Sephton and Botta 2005). The Sample Analysis at Mars instrument suite onboard the *Curiosity* rover analyzed Gale Crater mudstones and the detected inventory could contain the first potentially indigenous organic molecules on Mars. Chlorobenzene at 100s ppb levels and dichloroalkanes with up to four carbon atoms at 10s ppb levels were detected by heating up to <400 °C (Freissinet et al. 2015). Diverse products including aliphatic hydrocarbons, thiophenes, and aromatic hydrocarbons were also detected at ppm levels in pyrolysis products of macromolecular components at 500 °C to 820 °C (Eigenbrode et al. 2018). In addition, oxidized forms of organic carbon (CO_2 and CO) with abundances ranging from ~200 to 2,400 ppm in Gale Crater lake sedimentary rocks have also been measured by *Curiosity* (Sutter et al. 2017). A similar range of organic C abundances in clay-rich seafloor sediments from the South Pacific Gyre is known to support microbial populations with cell densities of 10^3 to 10^5

Table 2.2. Organic and inorganic carbon detected in samples of Mars, carbonaceous meteorites, Mars analogs on Earth and the Moon (simplified from Steininger et al. [2012] and references therein and updated using Agee et al. [2013]; Steele et al. [2016]).

Source	Sample	Organic carbon	Inorganic carbon (ppm)
Mars (in situ)			
Viking 1 &2	Soil	A few ppm	2–5 wt% (?) $MgCO_3$
Phoenix	Soil	No definitive detection	3–5 wt% $CaCO_3$
Curiosity Gale Crater	Aeolian sediments and sedimentary rocks (Cumberland mudstone)	Oxidized: 200–2400 ppm Reduced: 300 ppb chlorobenzene; 70 ppb dichloroalkanes	<0.7 wt% carbonates
Martian meteorites	14 specimens	Average: 18 (±26) ppm	
	Chassigny	Magmatic: 2.1 ppm	2.5 ppm C as carbonates
	Shergottites	Magmatic: Range: 2–110 ppm; Average: 4 ppm	?
	Nakhla	Organic: ~ 150 ppm	188 ppm C as carbonates
	ALH84001	Magmatic: 13 ppm; Organic: 47 ppm	337 ppm C as carbonates
	RBT 04262	Reduced organics: ~4 to 130 ppb amino acids	
	NWA 7034	22 (±10) ppm	?
Other meteorites (not Martian)	CI	3–5 wt%	?
	CM (mainly Murchison)	Macromolecules: ~ 1.5 wt.% C; Small organics: >400 ppm	400–2000 ppm C as carbonates; 400 ppm diamond; 7 ppm SiC
	Micro-meteorites	10–12 wt%	?
Moon			
Apollo sites	Soils and breccias	~ 100 ppm (highly variable)	
	Rocks	Up to 50 ppm	
Earth			
Atacama	Soils	32 ppm	1414 ppm

cells g^{-1} (D'Hondt et al. 2010, 2015). Yet the presence of reduced and oxidized carbon and organic compounds alone are not sufficient to indicate life. Reduced carbon has been found in meteorites from asteroids and from Mars (Table 2.2) and it is recognized that many nonbiological processes produce concentrations of reduced carbon and even when present in organic structures the involvement of life is not conclusively indicated. Organic carbon-rich meteorites from asteroids (Grady et al. 2018) are good examples of the widespread nature of nonbiological organic chemistry in the solar system (Sephton 2014) and most organic materials in Martian meteorites appear to indicate origins by nonbiological processes, including igneous, hydrothermal, and impact-based synthesis mechanisms (Steele et al. 2012, 2016). For example, trace levels (~4 to 130 ppb) of the straight-chain, amine-terminal *n*-ω-amino acids glycine, β-alanine, γ-amino-*n*-butyric acid, and δ-amino-*n*-valeric acid were identified in the Martian meteorite RBT 04262 and were argued to be nonterrestrial in origin based on their unusual relative abundances and absence in proteins compared to known terrestrial occurrences (Callahan et al. 2013). For the amino acids detected in RBT 04262 they displayed no significant enantiomeric excess (a property believed to be fundamental to life) and all were likely to have been formed by nonbiological processes; the dominance of straight-chained, amine-terminal amino acids (n-ω-amino acids) was inconsistent with Strecker synthesis and a Fischer–Tropsch/Haber–Bosch-type origin was inferred at elevated temperatures either during igneous processing on Mars or during impact ejection of the rock from Mars. Martian meteorites provide an excellent reference for abiotic organic chemistry on Mars that can be compared to organic matter found in samples returned from Mars. Irrespective of the possible nonbiological origins of the organic materials in meteorites from asteroids and Mars the utility of organic carbon for known and potential inner solar system biochemistries ensures that it retains its status as a key indicator of life. Once detected, confirmation of an origin from life is then readily recognized by examining the detailed chemical nature and context of any organic carbon detected.

2.1.2 Key Open Questions for Sub-Objective 2.1

How do Earth and Mars differ in their carbon reservoirs and fluxes? To understand Mars and its similarities and differences to Earth more completely is to understand its ability and likelihood of hosting life. Carbon on and in planets in the inner solar system is cycled through various reservoirs (Fig. 2.2). On Earth those reservoirs are the atmosphere; hydrosphere; geosphere; and importantly, the biosphere. On Mars, carbon is or has been cycled through its atmosphere, hydrosphere, and geosphere but the existence of a past or present biosphere is uncertain. There is no unambiguous evidence of past plate tectonic activity on Mars, stable surface water, or biological activity, characteristics that may be connected owing to the interdependence of element recycling/resupply and Earth's biological activity. The fluxes and reservoir sizes reflect the functioning of the Earth's biogeochemical cycle and therefore contain stable carbon isotopic evidence (represented by $\delta^{13}C$ values) of biological activity. Discerning the effects of biology on a carbon cycle requires an understanding of what biology-free baseline values would be expected. For the Martian carbon cycle, some insights have been gained from studies of Martian meteorites (Grady and Wright 2006; Steele et al. 2016) and models (Hu et al. 2015) but much more work must be done to provide the background required to allow similarly detailed interpretations such as those made for the carbon cycle on Earth.

How do Earth and Mars differences allow us to frame our investigations to detect Martian life? As with comparisons of the carbon cycles of Earth and Mars, an appreciation of what biology-free organic signals could

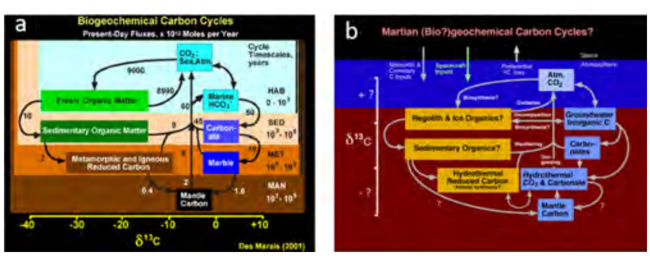

Fig. 2.2. (a) Earth's reasonably well-studied and understood carbon cycle (Des Marais 2001) and (b) a hypothetical Martian (bio?) geochemical carbon cycle, showing principal C reservoirs (boxes) in the mantle, crust, and atmosphere, and showing the processes (arrows) that might link these reservoirs (Des Marais 2004). In (a) the horizontal axis represents measured or calculated $\delta^{13}C$ values, while in (b) the vertical axis at left represents the wide range of $\delta^{13}C$ values that might exist between mantle carbon and carbon in atmospheric and near-surface reservoirs whose $\delta^{13}C$ values have increased due to isotopic fractionation caused by atmospheric escape of C species.

Table 2.3. Key open questions for Sub-Objective 2.1: Assessment and characterization of Martian carbon.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 2.1
How do Earth and Mars differ in their carbon reservoirs and fluxes?
How do Earth and Mars differences allow us to frame our investigations to detect Martian life?
How and why do the controls on preservation of organic carbon vary between Earth and Mars?
How might the probably punctuated and geographically limited nature of organic carbon on Mars affect our ability to determine PBS on returned samples?
What is the nature of potential organic bacteriomorphs on Mars compared to Earth, and what are the strategies to be utilized to separate real from fake PBSs?

be expected on Mars should be established. Any reduced carbon or complex organic molecules detected in samples from Mars should be extensively investigated for features that provide the ability to discriminate between nonlife and life sources and, preferably, between an origin on Earth and Mars. For detecting life, the usefulness of organic carbon to biochemistry is in its ability to form complex and specific organic structures that perform certain functions including energy storage, structural roles, and information-carrying tasks. Recognizing the organic signatures of life is therefore an achievable goal if preservation has taken place (e.g., Killops and Killops 2005). For discriminating provenance on Earth and Mars, one approach is to seek evidence of detailed chemical adaptations to the different environments. Although based on carbon and water the biochemical similarities between organisms on Earth and Mars would not be expected to be exact. Our terrestrial examples of environmental adaptations reveal substantial biochemical variations that reflect ecosystem diversity and the challenges and opportunities presented by the host environment (Sephton and Botta 2005) and, we could expect similar recognizable biochemical adaptations for any life on Mars (Table 2.3).

2.1.3 Why Returned Sample Studies Are Important for Sub-Objective 2.1

To investigate the Martian carbon cycles thoroughly and to interrogate any molecular indicators of nonbiological or biological processes, returning samples to Earth is a powerful strategy. In situ analyses on planets and ex situ measurements following the return of samples to Earth seek to achieve the same objective and are complementary methods. In situ activities on Mars represent a practically unlimited amount of sample accessed by limited analytical facilities. MSR delivers a finite amount of sample to a wide range of laboratories with the most sophisticated and comprehensive analytical techniques available. Moreover, once on Earth curatorial practices ensure that returned samples are never exhausted, with diminishing sample mass potentially offset by continuous future analytical innovation and improvement. Returned samples are managed so that they are the gift that keeps giving: a good example of returned, curated, and professionally distributed lunar material was provided by the Apollo missions (Allen et al. 2011). The number of publications in the literature from the Apollo effort is substantial and demonstrates the great and sustained benefit possible from sample return missions (Crawford 2012). The Apollo experience indicates that the scientific rewards from returned samples substantially enhance those from in situ activities. For missions such as MSR the advantages are likely to be more enhanced when compared to the Apollo experience. The characterization of organic materials in samples of Mars that are expected to be present in trace amounts of sample return would benefit from access to analytical techniques that will never be space-compatible due to restrictions in weight, size, and the need for complex sample preparation. For example, the use of organic solvents for extracting organic molecules from the crushed rock material is a key component for organic analysis on Earth. Because of environmental conditions on Mars, such as low surface pressure, these protocols are very hard to mimic on Mars. Even if one of these extraction protocols could be made Mars-compatible, the full range of protocols used on Earth involving many different solvents needed for extracting the full diversity of organic molecules, will never be available on Mars.

2.1.4 Sample Investigation Strategies to Achieve Sub-Objective 2.1

Four investigation strategies and 10 sets of measurements are defined to elucidate the nature of carbon chemistry on Mars. These strategies must enable a comprehensive characterization of any inorganic and organic carbon present. The nature of the organic carbon must also be fully revealed by effective assessments of its detailed molecular architecture, its stable isotopic composition and its association with its host environment (Table 2.4).

***Investigation Strategy 2.1A:* Develop as complete an inventory as possible of the organic molecules present in the samples, as well as any oxidized carbon compounds.**

Investigation Strategy 2.1A attempts to measure the presence, concentration, and characteristics of carbon in both oxidized and reduced forms on Mars. On our Earth, biogeochemical cycling transfers carbon between oxidized (e.g., carbon dioxide in our atmosphere and carbonate rock in our geosphere) and reduced reservoirs (e.g., the biosphere, carbonaceous rocks in the geosphere). The varying oxidation states of the carbon reservoirs on Mars provide context for assessing the mechanisms of carbon cycling on the planet and whether biological activity is a driver for the flux of material between reservoirs. Reduced carbon reservoirs (e.g., Fig. 2.3) may contain organic matter and that acts as a repository of information-rich molecular architectures that reveal synthetic mechanisms and therefore origins, including a potential variety or biological and nonbiological processes (Summons et al. 2014).

The examination of the co-association of organic matter relative to known mineral catalysts enables recognition of in situ and nonbiological formation of organic matter. For example, the Fischer–Tropsch synthesis involves the conversion of carbon monoxide

Table 2.4. Summary of sample-related investigation strategies to understand Martian carbon chemistry.

Investigation Strategies (IS) for Objective 2 Sub-Objective 2.1		
2	**Life**	**Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.**
2.1	Carbon chemistry	Assess and characterize carbon, including possible organic and prebiotic chemistry.
IS 2.1A	Develop as complete an inventory as possible of the organic molecules present in the samples, as well as any oxidized carbon compounds.	
IS 2.1B	Determine isotopic fractionation between organic matter and carbon-bearing minerals such as carbonates.	
IS 2.1C	Establish the indigeneity of any detected analytes.	
IS 2.1D	Identify any aspects of the environment potentially conducive to the existence and preservation of prebiotic chemistry and amenable to detection.	

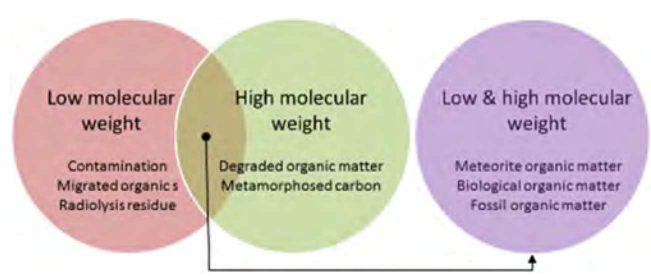

Fig. 2.3. Molecular weight combinations commonly observed for organic matter assemblages and some possible interpretations (Sephton et al. 2014).

or carbon dioxide to hydrocarbons to produce a Schulz–Flory distribution, a steep decrease of relative abundance for hydrocarbons with increasing molecular weight (Salvi and Williams-Jones 1997). Thermal metamorphism of carbonates alone can produce low molecular weight hydrocarbons alongside characteristic inorganic products such as calcium oxide and iron oxides (Giardini and Salotti 1969), and when carbonates and graphite react methane can be produced (Holloway 1984). Methane in the presence of serpentine (McCollom and Seewald 2001) may imply the production of hydrogen, from the hydration of olivine, which then combines with carbon dioxide to produce methane (Abrajano et al. 1990). The relative abundances of organic compounds are also a source of useful information. In the terrestrial biosphere a predominance of either short- or long-chain fatty acids or their diagenetic product alkanes can reveal the influence of marine or land plants, respectively (e.g., Killops and Killops 2005). Analogous environmental signals may be detectable in collected samples that record a Martian biosphere.

Table 2.5 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.1A and move toward understanding of Martian carbon chemistry.

Table 2.5. Samples and measurements implied by Investigation Strategy 2.1A.

Samples identified to advance Investigation Strategy 2.1A:

- Samples from environments listed in Objective 1 which contain organic matter in concentrations significantly above average, especially samples obtained from below the surface.
- Igneous rocks that have the potential for habitability or abiotic synthesis especially those inferred to have been recently exposed.
- Regolith.

Measurements identified to advance Investigation Strategy 2.1A:

- Measure the presence, concentration, and characteristics (e.g., redox state) of inorganic carbon including oxidized carbon (e.g., as carbonate) and reduced carbon (e.g., as graphitic or graphite-like carbon).
- Measure the presence, concentration, and characteristics of simple and complex molecules and polymers containing C, H, N, O, P, Cl, and S (organic carbon), and characterize organic matter features, including molecular structures (e.g., chirality), abundances and/or molecular weight distributions.
- Determine co-association of, and context for, organic matter relative to known minerals, especially mineral catalysts that produce organic material from C_1 gases.
- Measure cosmogenic nuclides to determine integrated surface exposure age and erosion rate.

***Investigation Strategy 2.1B:* Determine isotopic fractionation between organic matter and carbon-bearing minerals such as carbonates.**

Investigation Strategy 2.1B seeks to identify where variations in zero-point energies for stable isotopes have led to fractionation of those isotopes in chemical reactions. Commonly the lighter stable isotope is more reactive than the heavier stable isotope and is used preferentially in chemical reactions. The overall stable isotope ratio of pooled reaction products is often different from those of the starting materials and the degree of difference, known as the fractionation, reflects the specific reaction taking place and the relative sizes of the reservoirs. Enzyme-derived stable isotope fractionations associated with biochemistry can be used as diagnostic indicators of biological activity and help to distinguish biological organic products from their nonbiological counterparts. The Fischer–Tropsch type reaction is one example of a prebiotic mechanisms that displays modest fractionation (Johnson et al. 2012) and may be distinguishable from biological, enzyme-driven fractionations.

Table 2.6 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.1B and move toward understanding of Martian carbon chemistry.

***Investigation Strategy 2.1C:* Establish the indigeneity of any detected analytes.**

Investigation Strategy 2.1C seeks to identify false positives and false negatives associated with contamination. The abundance of organic molecules and other carbon phases in Martian samples can be expected to be low (Table 2.3) and can be easily overprinted by terrestrial organic compounds and carbon phases originating from sample collection on Mars, sample handling, and contamination of samples by terrestrial organisms. Previous studies of Martian meteorites have shown colonization of terrestrial organisms (Steele et al. 2000; Toporski and Steele 2007). Even with the greatest care in sample management it is likely that some contamination will take place

Table 2.6. Samples and measurements implied by Investigation Strategy 2.1B.

Samples identified to advance Investigation Strategy 2.1B:

- Samples listed from environments listed in Objective 1 that contain carbon (either oxidized or reduced) in concentrations significantly above average.

Measurements identified to advance Investigation Strategy 2.1B:

- Measure stable isotopic compositions (e.g., of C, H, N, O, P, S, Cl) in organic compounds in context with known isotopic pools.

(Summons et al. 2014). Therefore, previous and current missions to Mars have established highest acceptable levels of allowed terrestrial organic contaminants (expressed as both total organic carbon (TOC) and individual compound classes) (Summons et al. 2014). Other important tools for tracking potential organic terrestrial contamination during sample collection and handling are witness plates and contamination knowledge for common terrestrial contaminants.

Similarities between carbon chemistry on Mars and Earth would make discriminating between the two sources difficult. Various ways have, however, been developed in order to determine if carbon phases found in Martian samples are indigenous or later introductions. One important tool is to determine the D/H ratio of organic matter, which for Martian material has been shown to be well above terrestrial values (Owen et al. 1988). Further diagnostic information may be forthcoming from organic matter–mineral associations that imply indigenous processes rather than the general addition of contamination. For example, a homogenous distribution of an organic compound, commonly found on Earth, such as polycyclic aromatic hydrocarbons, across a surface containing heterogeneous mix of minerals, would strongly suggest the addition of terrestrial contaminants (Stephan et al. 2003).

Table 2.7 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.1C and move toward understanding of Martian carbon chemistry.

***Investigation Strategy 2.1D:* Identify any aspects of the environment conducive to the existence and preservation of organic chemistry and amenable to detection.**

Organic carbon–based records require suitable conditions for their preservation. The preservation of organic matter is a well-studied subject in Earth environments and it is recognized that oxidation is the major degrading mechanism that can remove signatures diagnostic of provenance, making discrimination progressively more difficult and eventually impossible (e.g., Fig. 2.4). On Earth, an association with fine-grained minerals protects organic matter by excluding oxidants (Tyson 1995). Adsorption on mineral surfaces also makes organic matter less available for oxidation and the high surface areas of fine-grained minerals provide additional protection (Keil et al. 1994). Other minerals that can promote organic preservation include sulfates (Aubrey et al. 2006), iron oxides (Parenteau et al. 2014; Lewis et al. 2018), and silica (Westall et al. 2011a, 2011b). The matrices in which organic compounds, including biosignatures, are preserved vary in their resilience; unstable matrices include ice or salts, while silica or phosphate is highly resistant (Farmer and Des Marais 1999).

Table 2.7. Samples and measurements implied by Investigation Strategy 2.1C.

Samples identified to advance Investigation Strategy 2.1C:

- Samples from environments listed in Objective 1 which are found to contain carbon and reference materials of all material and substances that could have been contact with samples.

Measurements identified to advance Investigation Strategy 2.1C:

- Evaluate the indigenous nature of any detected carbon and organic molecules. Rule out terrestrial sources of carbon and organic molecules.

If present, organic matter associated with both nonlife and life processes could be expected at the surface of Mars where biological production, meteoritic infall, or in situ synthesis can occur. Once present at the surface of Mars, organic matter would be subjected to processes that lead to its degradation. The Martian surface is exposed to multiple radiation types. UV photolysis has been shown to be an effective destroyer of organic matter in the Atacama Desert on the time scales of Martian days but mineral hosts such as calcite, calcium sulfate, kaolinite, and clay minerals can provide protection from photolysis and promote preservation (Ertem et al. 2016). Ultraviolet radiation–driven photochemistry has also been shown to produce

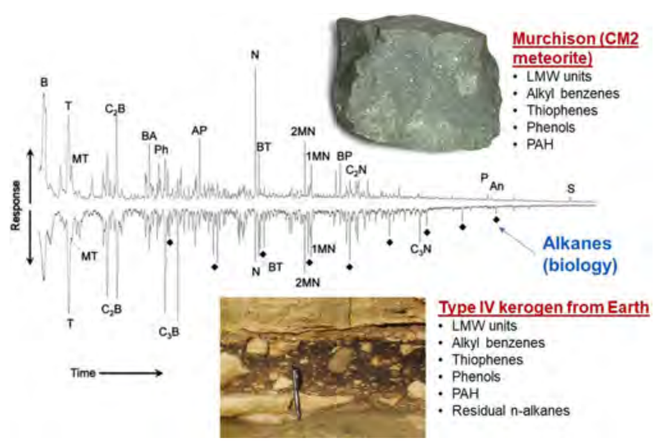

Fig. 2.4. Detailed side-by-side comparison of total ion currents of pyrolysis products (600 °C, single step) of degraded but ultimately biological type IV kerogen, and Murchison, a type CM2 carbonaceous chondrite. The key responses from the nonbiological organic matter in the meteorite are also present in data from the degraded biological type IV kerogen. Yet, some discernable biogenic character remains in the type IV kerogen (e.g., presence of alkanes [◆] and isomeric arrangements for substituted benzenes (C_2B and C_3B). Image after Matthewman et al. (2013).

oxidized minerals (Klein 1978) including perchlorate (Carrier and Kounaves 2015). Photolysis in the presence of minerals can accelerate the degradation of organic matter owing to catalytic processes. Minerals containing ferrous iron (Dos Santos et al. 2016), magnesium oxide, and forsterite (Fornaro et al. 2013) lead to reduced half-lives for biologically relevant organic compounds in UV irradiation experiments.

One way to acquire samples unaffected by oxidation and irradiation is to search for samples that have been recently delivered from the subsurface by natural processes such as impacts (Cockell and Barlow 2002). Yet, this apparent advantage comes at a cost and organic preservation can be frustrated by the impact ejection process. High impact-related pressures appear to introduce sample bias where long-chain hydrocarbon structures are degraded relative to aromatic structures (Montgomery et al. 2016). Degradation of organic signals can also occur during the analysis of samples. To date all in situ life detection missions to Mars have utilized thermal procedures to isolate organic matter from samples (Biemann et al. 1977; Mahaffy et al. 2012). Unfortunately, oxidizing minerals such as perchlorates (Mahaffy et al. 2012) and sulfates (Lewis et al. 2015) decompose during heating to release oxygen that promotes combustion of any organic matter present. The return of samples to Earth would provide opportunities to avoid oxidation-related analytical issues. It should also be noted that prebiotic chemistry is unlikely to survive in a nascent or established biological world. Prebiotic organic compounds would be exploited by existing organisms, a consequence that was recognized by Charles Darwin who stated that such compounds would be instantly devoured (Darwin and Darwin 1887).

In the context of Mars 2020, collecting samples in areas that are actively eroding would help to increase the chances of finding preserved organics that have been recently exposed. Results from MSL at Gale Crater show that preserved organics can be found in the very near subsurface if searched for in the right locations (Freissinet et al. 2015; Eigenbrode et al. 2018). The three remaining Mars 2020 candidate landing sites are all actively eroding, although they also represent different depositional environments in terms of dust deposition. The SHERLOC instrument on M-2020 will have the capability to detect and determine the spatial distribution of a wide range of organic compounds in order to aid in sample selection as well (Abbey et al. 2017; Beegle et al. 2015).

Table 2.8 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.1D and move toward an understanding of Martian carbon chemistry.

Table 2.8. Samples and measurements implied by Investigation Strategy 2.1D.

Samples identified to advance Investigation Strategy 2.1D:
- Rocks of any type (including samples listed in Sub-Objective 1-1) that have been recently exposed (and thus protected from radiolysis until recently), especially those whose formation age predates the cessation of the planetary magnetic dynamo.

Measurements identified to advance Investigation Strategy 2.1D:
- Identify potential components of prebiotic chemistry (e.g., prebiotic organic carbon compounds, reactive phosphorous, etc.
- Identify the association of any organic carbon relative to known mineral catalysts and catalysis pathways.
- Assess organic inventory for similarity to known abiotic processes such as Strecker synthesis or Fischer–Tropsch-type reactions.
- Measure cosmogenic nuclides to determine surface exposure age and erosion rate.

2.2 Sub-Objective 2.2. Assay for the Presence of Biosignatures of Past Life at Sites That Hosted Habitable Environments and Could Have Preserved Any Biosignatures

ASSAY FOR THE PRESENCE OF BIOSIGNATURES OF PAST LIFE	
Why is this objective critical?	*The search for life is one of the driving objectives for Mars exploration in general, and sample studies are an essential component of astrobiology strategy.*
Which are the most important samples?	*All of the samples collected as part of Objective 1 are of interest.*

2.2.1 Introduction and Current State of Knowledge

Seeking life beyond Earth is one of the great endeavors of humankind. It pushes us to probe frontiers of knowledge, space and time toward understanding our origin and whether we are alone in the Universe. Mars has long been identified as most Earth-like among the planets. Indeed, there is now strong evidence that Mars was likely to have been habitable early in its history (Objective 1), when water was present on its surface at the same time as life was taking hold on Earth. This knowledge from earlier discoveries has fueled interest in exploring for a fossil biosignature record in ancient Martian terrains.

A biosignature (a "definitive biosignature") is an object, substance and/or pattern whose origin specifically requires a biological agent (Des Marais et al. 2008; Mustard et al. 2013). One key example is complex organic molecules and/or structures whose formation and abundances relative to other compounds are virtually unachievable in the absence of life (e.g., Cronin and Walker 2016). A potential biosignature is an object, substance, and/or pattern that might have a biological origin and therefore compels investigators to gather more data before reaching a conclusion as to the presence or absence of life. The usefulness of a potential biosignature is therefore determined not only by the probability that life created it but also by the improbability that nonbiological processes produced it. Accordingly, because habitable planetary environments could create nonbiological features that mimic biosignatures, these environments must be characterized to the extent necessary to provide a context for scientific interpretations (Objective 1).

To be useful for exploration, biosignatures must be defined in ways that not only tie them to fundamental attributes of life but that also allow them to be measured and quantified. Universal attributes of life on Earth include complex interacting physical and chemical structures, the utilization of free energy and the production of biomass (both organic structures and inorganic mineral phases) and wastes, and phenomena that can be sustained through self-replication and evolution. However, because of selective preservation we cannot expect all of the universal attributes of life to be expressed in ancient planetary materials. Useful biosignatures must be both preserved and amenable to detection (Hays et al. 2017). Examples of physical structures include individual cells and communities of cells (e.g., colonies, biofilms, and mats) and their fossilized counterparts (mineral-replaced and/or organically preserved remains). Biominerals are inorganic mineral structures that have functional uses (e.g., magnetosomes in magnetotactic bacteria). Biomass and its organic products are structural, functional, and information-carrying organic molecules that characterize life forms (e.g., on Earth these include lipids, proteins, and nucleic acids). The utilization of free energy and the production of biomass leave characteristic imprints upon the environment of the processes by which life extracts energy and material resources to sustain itself—e.g., rapid catalysis of otherwise sluggish reactions, isotopic discrimination, mineral formation influenced by biological activity, and enrichment or depletion of specific elements. Another identified type of metabolic biosignatures is the metallome, the metallic load of elements associated to living organisms (Zerkle et al. 2005), which indicates that basic biochemical reactions are achieved by only few metalloenzymes. Significantly, examples can be found of abiotic features or processes that can resemble biological features in each of these categories. However, finding a suite of independent features can provide more robust evidence of biology. In addition, biologically mediated processes are distinctive due to their speed, selectivity, and a capability to invest energy into the catalysis of kinetically inhibited processes or the handling of information. These processes can create features that can in turn be recognized as having biological origins.

Earth and Mars are quite similar in terms of planetary conditions and chemistries, in comparison to, for example, gas giants or icy moons. This similarity suggests that differences in life forms that originated independently on Earth and Mars would likely occur at a secondary, rather than first-order level, and therefore are NOT likely to differ at the fundamental levels of biochemical scaffolding (alternatives to carbon), or required solvent (alternatives to water). However, differences from terrestrial life become increasingly possible, and ultimately probable, with increasing levels of biochemical specificity (e.g., nucleic acids and peptides). Indeed, considering that on Earth, a considerable amount of biological evolution unfolded prior to the rise of LUCA (the Last Universal Common Ancestor), several of the fundamental primitive biomolecules, especially nucleic acids, might have been different from the current ones. Such possible primitive biomarkers might also be taken into account when analyzing Martian samples.

Highly diagnostic biosignatures recognized in studies of terrestrial systems commonly represent extremely specific attributes of biochemistry (e.g., specific lipids or particular sequences of amino or nucleic acids in the case of molecular biosignatures). Although such specific markers of life would be unquestionably valuable if detected on Mars, the likelihood that the same markers (e.g., the same specific choices of biomolecules) would arise through an independent origin and elaboration of life seems low (notwithstanding the potential for evolutionary convergence). Even though life detection strategies for Mars should ideally allow for the detection and characterization of Earth-like biosignatures, the highest priority should be given to approaches and methods that define and seek biosignatures in the broad, universal sense.

The types of currently recognized biosignatures are examples of objects, substances, and/or patterns whose origins specifically require biological processes, and they can occur over a range of spatial scales (e.g., Farmer 1999). The M-2020 SDT (Mustard et al. 2013) report identified the following categories of biosignatures: organic biomolecules, stable isotopic patterns, minerals, chemicals, and macroscale and microscale fabrics and structures (e.g., stromatolites, microfossils). Active

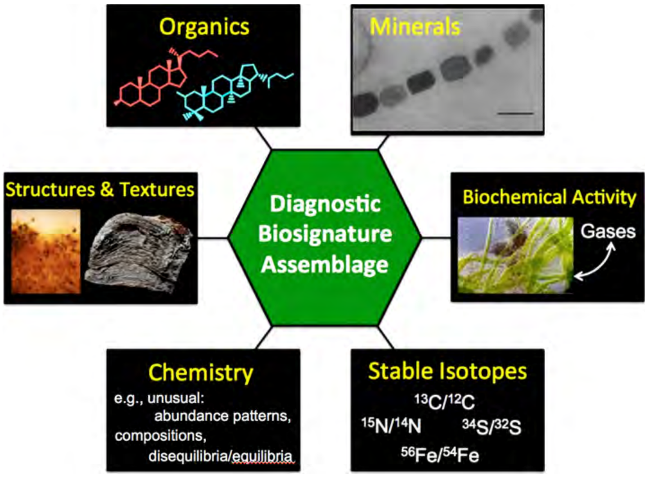

Fig. 2.5. Categories of biosignatures to be sought in suites of samples returned from Mars. Section 2.3 addresses the Biochemical Activity category.

biological processes are an additional category (see Section 2.3)—*Viking* mission's life detection experiments searched for these processes (Klein 1978). Figure 2.5 indicates the six categories of biosignatures to be sought during a MSR campaign.

2.2.2 Key Open Questions for Sub-Objective 2.2

The search for biosignatures on Mars must address the array of important issues outlined above. Biosignatures must reflect fundamental attributes of life as we currently understand it. These include complex interacting biophysical and biochemical structures, the utilization of free energy, the production of biomass and wastes, and phenomena that can be sustained through self-replication and evolution. To be useful for exploration, biosignatures must also be measurable and quantifiable, for example, as physical structures, substances, patterns, or combinations of these attributes. But habitable planetary environments can create nonbiological features that mimic biosignatures, and some environmental processes can alter or destroy them. Yet other processes can preserve biosignatures. Accordingly, we must characterize the environmental attributes, both past and present, of potential sites of exploration in order to evaluate their potential for preserving any biosignatures and to inform our scientific interpretations. Table 2.9 identifies the key questions that arise from these considerations.

2.2.3 Why Returned Sample Studies Are Important for Sub-Objective 2.2

As has been learned from studies of the early fossil record on Earth, the combination of field investigations and detailed laboratory analyses is required to confirm potential biosignatures in early Archean rocks (4000–3200 million years ago, Ma), as various postdepositional processes often have obscured or may even have destroyed signs of life (e.g., Brocks and Summons 2003; Djokic et al. 2017). Indeed, evidence for Archean-age life is often equivocal and contentious (e.g., Brasier et al. 2002, 2005; Schopf et al. 2002; Marshall et al. 2011; Schopf and Kudryavtsev 2012; Nutman et al. 2016; Dodd et al. 2017). Compelling arguments typically emerge from multiple lines of evidence that include geologic and paleoenvironmental contexts, sophisticated high spatial resolution imagery, and in situ geochemical analyses (e.g., Westall et al. 2011a, 2011b; Muscente et al. 2018). The same is likely to be true of any potential biosignatures discovered in ancient rocks by future rovers or human-led missions to Mars. Returned samples from Mars would allow for such analyses to be performed that would otherwise not be possible using rover instruments, although as noted, the M-2020 instrument suite will provide essential context for the cached samples. In other words, proof of Martian life, if it ever existed, will only emerge from discoveries made in laboratories on Earth. The broadest, most rigorous investigations of potential biosignatures (PBS) can only be achieved in Earth-based laboratories (Fig. 2.6). This seems required before the scientific community is inclined to accept any potential biosignatures as definitive biosignatures. State-of-the-art laboratory instrumentation typically requires sophisticated sample preparation techniques that, in turn, require initial laboratory-based observations that guide the selection and adaptation of these techniques.

As best practices improve for avoiding/isolating contamination and understanding complex features in samples, state-of-the-art analyses would be invoked. These features will occur across a vast range of size scales and abundances, from the macroscopic to the molecular. Potentially diagnostic attributes of samples and include the following: (1) preservation and degradation ("taphonomy") of microscale features; (2) organic molecular structures—including their relative

Table 2.9. Key open questions for Sub-Objective 2.2: Assay for the presence of biosignatures of past life.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 2.2
What processes are key for preserving, altering or destroying any Martian biosignatures?
What are the attributes of physical structures that could be interpreted as biosignatures?
What are the attributes of substances that could be interpreted as biosignatures?
What physical, chemical and isotopic patterns could be interpreted as biosignatures?

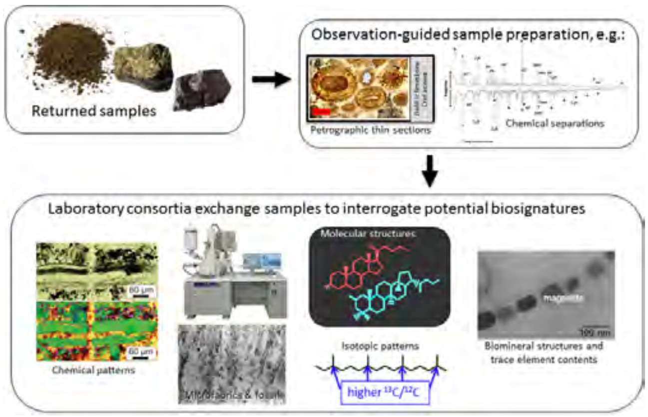

Fig. 2.6. Potential biosignatures can be investigated thoroughly only by observation-guided sample preparation, followed by investigations by laboratory consortia that apply state-of-the-art techniques.

abundances, diastereo-isomeric and structural isomer preferences, chirality, etc., all down to subnanomole abundances; (3) stable isotopic abundance patterns within molecules and between molecules, compound classes and minerals—down to nanomole abundances; (4) mineral diversity and trace element contents—down to submicrogram abundances; (5) rock fabrics (and biological?) structures—from submicron to centimeter scales; (6) inorganic chemistry—microscale compositional and spatial patterns.

Potential biosignatures in early Earth paleoenvironments require multiple lines of evidence to be accepted by the scientific community as definitive biosignatures. Accordingly, a single prepared sample often must be shared between multiple laboratories and analytical instruments in order to achieve the most definitive interpretations.

2.2.4 Sample Investigation Strategies to Achieve Sub-Objective 2.2

To be useful for exploration, potential biosignatures must be both measurable and quantifiable. For each of the categories indicated in Fig. 2.5, the potential for the observed features to be biological varies significantly over a broad range of observations. For example, any observation of sedimentary reduced carbon could be biological in origin and thus would be regarded as a potential biosignature. Although the presence of such a deposit alone is not diagnostic of a biological origin, different types of observations could distinguish biotic from abiotic organic matter with varying degrees of confidence. For example, molecular compositions, chirality, molecular patterns, along with other potential biosignatures such as complex morphology, may provide an extremely high level of confidence, based on Earth-analog settings (Summons et al. 2011; Westall et al. 2011a, 2015a). Ideally tests for biogenicity would be based on multiple lines of evidence at a given site explored by rovers equipped for sample caching and return. The potential for biosignature preservation needs to be evaluated for each paleoenvironment targeted for analysis because the processes that determine high-quality preservation versus modification or destruction of a particular signal vary with category, rock type, environment, and postdepositional history (see Sub-Objective 1.4).

All of the investigations in this section would make use of the sample suite(s) identified as part of carrying out Objective 1. We have identified six investigation strategies and 18 sets of measurements to assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures (Table 2.10).

Investigation Strategy 2.2A: ***Characterize aspects of the environment that are conducive to the preservation or degradation of biosignatures.***

To the extent that sediments, cements, and other surface materials have escaped alteration after their formation, they can preserve information about earlier environmental conditions and, potential biosignatures (Summons et al. 2011). Certain minerals and rock types (e.g., silica, carbonates, phosphates, phyllosilicates,

Table 2.10. Summary of sample-related investigation strategies to assay for possible biosignatures of ancient Martian life.

Investigation Strategies (IS) for Objective 2 Sub-Objective 2.2		
2	**Life**	**Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.**
2.2	Biosignatures—ancient	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.
IS 2.2A	Characterize aspects of the environment that are conducive to the preservation or degradation of biosignatures.	
IS 2.2B	Determine the presence and nature of any organic potential biosignatures.	
IS 2.2C	Characterize any patterns of stable isotopic abundances that might indicate biological processes.	
IS 2.2D	Identify any minerals that might indicate biological processes.	
IS 2.2E	Identify any morphological evidence of life.	
IS 2.2F	Identify any chemical evidence of life different from that specified above.	

evaporite minerals, etc.) are particularly conducive to preservation (e.g., Farmer and Des Marais 1999). Preservation can be compromised by weathering and erosion or by alteration in situ by oxidation, radiation, heating, and migrating fluids (Summons et al. 2011). For example, on Earth, nearly all portions of hydrothermal systems may be inhabited by microbial life, although preservation of an enduring geological record in "deep time" (hundreds of millions to billions of years old) depends on the intersection of favorable and sometimes fortuitous factors (e.g., Guido and Campbell 2011; Sillitoe 2015; Westall et al. 2015b).

This investigative component addresses preservation quality of potential biosignatures. Postdepositional diagenesis and geological activity have significant impacts on whether biosignatures are expected to be pristine, or whether they have been modified and could still be distinguishable. For example, microbial macro-textures commonly are preserved in siliceous and calcareous hot-spring deposits on Earth. However, high-quality, microscale preservation of biosignatures—producing convincing fossil biosignatures—depends on timing of mineralization (e.g., early silicification (Campbell et al. [2015a, 2015b] and references therein; Djokic et al. 2017), type of overprinting (e.g., acidic fluids with drop in phreatic level, or regional late silicification), and whether late diagenetic processes have been local or regional in extent (e.g., Walter et al. 1996; Guido and Campbell 2009, 2011, 2017). Mapping the diagenetic stage (e.g., Lynne and Campbell 2003; Jones and Renaut 2007), textural quality, and geochemical concentrations of relevant minerals and elements—at the microbial scale (e.g., Westall et al. 2015a, 2015b)—may be achieved with carefully selected returned samples.

Because of Mars's thin atmosphere and absence of a global magnetic field, cosmic radiation affects the preservation of organic biosignatures that have been situated within a few meters of the surface for tens of millions of years or longer (Pavlov et al. 2012). Accordingly, samples should be sought that have been stored more deeply for most of their history, and their status should be validated by measuring cosmic ray exposure ages.

Table 2.11 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2A and move toward an assay of possible biosignatures of ancient Martian life.

Table 2.11. Samples and measurements implied by Investigation Strategy 2.2A.

Samples identified to advance Investigation Strategy 2.2A:

- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.2A:

- Determine the presence of phases (e.g., silica, carbonates, phosphates, phyllosilicates, evaporite minerals, etc.) that are conducive to preservation.
- Identify evidence for postdepositional diagenetic alteration of sedimentary or hydrothermal deposits.
- Measure cosmogenic nuclides to determine surface exposure ages and erosion rates.

***Investigation Strategy 2.2B:* Determine the presence and nature of any organic potential biosignatures.**

As the major component of living tissue, organic matter is likely to retain diagnostic evidence about the nature of carbon-based reactions on Mars. Concentrations of organic matter, especially in environments in which organic compounds are exposed to oxidative processes, imply a replenishment mechanism that might be biological (Lovelock and Kaplan 1975). Biology uses enzyme-driven reactions to generate organic entities that are biochemically useful while nonbiological reactions are rarely as specific in the generation of their products. One celebrated example of organic specificity is amino acid homochirality, where biology on Earth is dominated almost exclusively by one enantiomeric form (Bada and McDonald 1996).

Diagnostic organic molecules (biomarkers) are probably the most definitive category of biosignatures. The geologic record of Earth's biosphere provides several examples. Anomalously high relative abundances of specific organic molecules in a rock can constitute evidence of a biological origin. For example, our biosphere is dominated by membrane fatty acids having 16 and 18 carbon atoms because these particular fatty acids impart favorable properties to cellular membranes. Analogous membrane lipids on Mars may reveal the influence of life. Detailed analyses of organic molecular structures can reveal information concerning the taxonomic affinities of ancient biota on Earth (with varying degrees of specificity), their physiologies, the environmental conditions that prevailed in the depositional environment, and the thermal maturity of the host organic matter (Killops and Killops 2005). Important organic molecules indicative of life (especially if associated with other biosignatures such as morphological structures) include proteins, nucleic acids (DNA and RNA) for extant life and amino acids, sugars, porphyrins, nucleobases, and lipids for both extant and extinct life (Engel and Macko 1993). For some molecules, for example, amino acids and fatty acids, the presence of the molecules themselves does not represent conclusive evidence for life and it is necessary to look at distributions of the molecules (e.g., Killops and Killops 2005; Georgiou and Deamer 2014). Such distributions include chain-length preference in lipids (increased intensity of even over uneven fatty acids and uneven over even alkanes) and homochirality of sugars and amino acids. For example, life on Earth uses left-handed (L) amino acids and right-handed (D) sugars. Important biomarker groups include membrane lipids such as hopanoids, sterols, and archaeols, and their diagenetic products. Additional biosignatures include the molecular distribution of organic molecules combined with the isotopic signature of specific molecules. Ecosystems can be delineated by the presence of domain-specific organic compounds with recognizable evolutionary advances in biosynthetic processes. Our biosphere recorded such advances with isoprenoid, hopanoid, and steroid lipids reflecting archaea, bacteria, and eukarya and their progressively complex biosynthetic pathways, and may therefore be used for taxonomical assignments of these domains. (e.g., Killops and Killops 2005; Des Marais and Jahnke 2018). Effective measurements of the relative abundances of organic compounds would be facilitated by sample return, owing to the higher sensitivity and resolution of Earth laboratory-based systems.

Another organic biosignature identifiable in terrestrial and potential returned Martian rocks is the association of organic carbon with the surfaces of volcanic sedimentary particles or volcanic rocks. Chemotrophic microorganisms colonize these kinds of surfaces: lithotrophs extract nutrients from them and obtain energy from redox reactions at their surfaces, sometimes leaving tell-tale corrosion tracks (Thorseth et al. 2003). Under favorable circumstances, such as abundance of nutrients, once moribund, they will be colonized in turn by organotrophs (Thorseth et al. 2001). They can be preserved in situ as a carbon coating on the surfaces of the particles, which can be encapsulated in a mineral cement and thus preserved. Thus, association of organic carbon with the kind of detrital particle or mineral surface that is metabolically useful for microbial metabolism could be considered as an interesting signature to be further explored with in situ high-resolution techniques. Examples exist from the early Earth in which volcanic particles were colonized and corroded by microbes and rapidly preserved by silicification (Westall et al. 2011b, 2015b; Foucher et al. 2010).

Table 2.12 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2B and move toward an assay of possible biosignatures of ancient Martian life. Objective 2.1 presents additional details regarding diagnostic molecular attributes and gives examples of relevant measurement techniques.

Table 2.12. Samples and measurements implied by Investigation Strategy 2.2B.

Samples identified to advance Investigation Strategy 2.2B:

- Samples from environments listed in Objective 1 that contain appropriate mineral assemblages, especially those samples that contain relatively abundant organic carbon.

Measurements identified to advance Investigation Strategy 2.2B:

- Measure the abundances of organic macromolecules and smaller molecules and characterize their attributes, including molecular structures, abundances, and/or molecular weight distributions.
- Measure the relative abundances of species containing C, H, N, O, P, and S.
- Evaluate the spatial relationships between organic matter and minerals and volcanic particles, especially such minerals that are compositionally and morphologically associated with biological activity or catalytic activity on Earth (e.g., Fe oxides and sulfides).
- Evaluate the relationship of potentially biogenic minerals and their associated organic material to the history of the host rock.
- Evaluate measurements of chemical and isotopic compositions of organic compounds to determine their conditions of formation and to seek evidence of chemical equilibria or disequilibria that are inconsistent with abiotic processes, and thus would be indicative of biological activity. Examples include widespread amino acid homochirality.

***Investigation Strategy 2.2C:* Characterize any patterns of stable isotopic abundances that might indicate biological processes.**

Patterns of stable isotopic ratios within suites of potential biosignatures can indicate conditions of formation and alteration (e.g., Shaheen et al. 2014; Williford et al. 2016) and provide evidence of chemical equilibria or disequilibria that is inconsistent with abiotic processes and thus might indicate biological activity (e.g., Hayes 2001). The sulfur isotope and oxygen triple isotope compositions of sulfates and any sulfide minerals can be diagnostic, as can the carbon isotopes and the triple oxygen isotopes in carbonates (e.g., $CaCO_3$, $MgCO_3$, $FeCO_3$). The isotopic abundances of metals whose redox state can be affected by biological processes (e.g., Beard et al. 1999) are also informative.

The $^{13}C/^{12}C$ values of bulk organic matter are a summation of its individual molecular components. Some of the most dramatic examples of isotopic discrimination are associated with the enzyme-directed reactions (Hayes 2001). Differences in stable isotope ratios of elements can be used, therefore, as potential

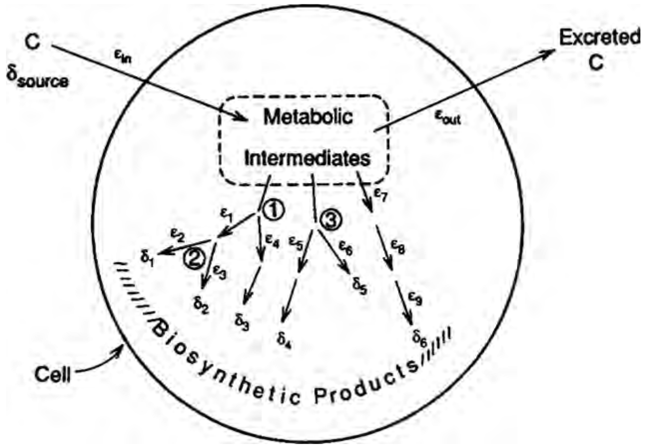

Fig. 2.7. A schematic representation of the stable carbon isotopic fractionations associated with biological processes (Hayes 1993). Kinetic isotope effects are indicated by "ε," stable isotope ratio values are represented by "δ", and branch points in carbon flow are indicated by numbers in circles.

indicators of biological processes. The $^{13}C/^{12}C$ values of biological organic matter are determined by a series of processes (Fig. 2.7) as follows (1) the $^{13}C/^{12}C$ value of the carbon source, (2) isotopic discrimination associated with the assimilation of carbon, (3) isotopic discrimination associated with metabolism and biosynthesis, and (4) partitioning of carbon isotopes at branch points in the metabolic reaction network (Hayes 1993). The accumulated fractionations can lead to $^{13}C/^{12}C$ values of biomass and individual biochemicals that are distinctly lower than that of the carbon source by predictable and measurable amounts. Stable isotopic fractionation can also lead to relationships between individual organic compounds that reflect metabolic and biosynthetic processes that are detectable using compound-specific isotope ratio methods. On Earth, $^{13}C/^{12}C$ patterns between organic phases and carbonates, and between individual organic and inorganic carbon compounds reflect contributions by phototrophs, chemotrophs, and microbial diagenesis (Des Marais and Canfield 1994; Williford et al. 2016). These patterns are distinct from patterns in nonbiological organic matter such as those found in carbonaceous meteorites in which the range of $^{13}C/^{12}C$ values is much greater (Sephton and Gilmour 2001).

Examples of methods for carbon-bearing minerals and other inorganic phases include isotope mass spectroscopy (MS) and laser spectroscopy; these should be able to target individual minerals and other phases. Examples of relevant methods for organic matter include MS, gas chromatography-MS, and laser spectroscopy. High-resolution isotope ratio mass spectrometry is one of the best tools for identification of

Table 2.13. Samples and measurements implied by Investigation Strategy 2.2C.

Samples identified to advance Investigation Strategy 2.2C:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.2C:
- Measure patterns of stable isotopic compositions of carbon-bearing minerals and other inorganic phases.
- Measure isotopic compositions of bulk organic matter and also patterns of isotopic abundances between organic compounds and within individual compounds.

isotopic fingerprints of biological molecules. Additionally, site-specific isotopic patterns of C, O, and N that are characteristic of biomolecules are currently measurable only for samples that are returned to Earth-based laboratories. Table 2.13 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2C and move toward an assay of possible biosignatures of ancient Martian life.

***Investigation Strategy 2.2D:* Identify any minerals that might indicate biological processes.**

Minerals form as products of local chemical and physical conditions, and more than 5300 minerals have been formally recognized (see http://rruff.info/ima for a recent list). This vast array of crystalline compounds indicates diverse modes of formation—consequences of diverse physical, chemical, and/or biological environments. For example, because some carbon-bearing minerals probably occur exclusively as a result of biological activity (Hazen et al. 2008), they represent promising biosignatures on Earth and possibly elsewhere. Suites of oxidized weathering minerals formed following the Great Oxidation Event, therefore they are likely to have been direct consequences of biological processes operating at a global scale. Quoting from Hazen et al. (2008): "Biological processes began to affect Earth's surface mineralogy by ~3.85–3.6 Ga, when large-scale surface mineral deposits were precipitated under the influences of changing atmospheric and ocean chemistry Multicellular life and skeletal biomineralization irreversibly transformed Earth's surface mineralogy. Biochemical processes may thus be responsible, directly or indirectly, for most of Earth's known mineral species."

Minerals and volcanic particles should be sought that, on Earth, are compositionally and morphologically associated with biological activity or catalytic activity (e.g., carbonates, sulfur minerals, phosphates, phyllosilicates, transition metal oxides, etc.), relative to the rock's texture and any organic carbon. Mineral assemblages can document the constituents and

Table 2.14. Samples and measurements implied by Investigation Strategy 2.2D.

Samples identified to advance Investigation Strategy 2.2D:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.2D:
- Detect individual minerals and map the spatial arrangements between minerals in formerly habitable environments.
- Determine the relationships between potentially biogenic minerals and the history of the host rock.

environmental conditions that accompanied the formation of a geological deposit. These assemblages also reflect the processes that subsequently altered the rock and thereby provide insights into the history of local crustal environments. Relevant measurement methods include XRD, electron microscopy, and IR spectroscopy. Table 2.14 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2D and move toward an assay of possible biosignatures of ancient Martian life.

***Investigation Strategy 2.2E:* Identify any morphological evidence of life.**

There exists a variety of morphological evidence for life that include, going from the macroscopic to the microscopic scale, (1) microbially induced or influenced structures and textures, such as certain sinter textures, as well as clotted fabrics produced by chemotrophic colonies (thrombolytic textures), (2) biofilms, (3) microbial colonies, and (4) microbial cells. Different analytical approaches are needed depending upon the spatial scale of the feature. Thus, the search for biosignatures would entail cataloging of spectral signatures in aqueous sedimentary rocks/minerals at a site, followed by selection of areas for targeted in situ observations that could produce spatially integrated maps of mineralogy and macro- and microtextures. Such mapping would help to evaluate whether facies (i.e., environmental) models of Earth's aqueous sedimentary systems provide appropriate analogs for analogous deposits on Mars.

A recent example at the macroscopic scale highlighting this approach is illustrated by study of the hydrothermal opaline silica deposit discovered by *Spirit* rover in Gusev Crater (Squyres et al. 2008), which contains unusual, knobby, digitate structures inferred as a morphological PBS (Ruff et al. 2011). Comparison with siliceous hot-spring deposits (sinter) at El Tatio geothermal field in Chile reveal close similarities with respect to textures and mineral spectra (Ruff and Farmer 2016), thereby strengthening the environmental framework and interpretation of the possible biotic nature of the structures. In particular, the knobby silica features at El Tatio constitute microstromatolites, entombing bacterial filaments within spring-derived hydrothermal silica (Fig. 1.7). In analogous features forming in New Zealand hot springs, rapid silica cementation of microbially excreted EPS (exopolymeric substance) created a fabric consisting of fine siliceous laminae that alternate with filamentous horizons (Handley et al. 2005, 2008).

Volcanic sediments in hydrothermal environments on the early Earth provide other examples of morphological evidence of the type of anaerobic, chemotrophic life forms that we expect on Mars. For example, several cm thick nutrient-rich layers of hydrothermally fed volcanic sediments from the 3.33 Ga Josefsdal Chert, Barberton Greenstone Belt exhibit a clotted, thrombolitic, carbonaceous texture, visible at the macroscopic and microscopic scales. The features are caused by heavy microbial colonization of volcanic particles (Westall et al. 2015a, 2015b). In situ elemental, carbon, and mineral mapping documents the close association of organic carbon with the volcanic particle surfaces, showing at the same time irregularities in the surface coatings that could not be produced by abiotic processes. In this case, individual cellular fossils were not preserved. However, microbial colonization of volcanic particle surfaces from more oligotrophic environments (i.e., poorer nutrient resources) in the 3.45 Ga Kitty's Gap Chert, Pilbara Greenstone Belt, was much weaker and the individual microbial cells were well preserved by rapid silicification from the silica-saturated Archean seawaters (Westall et al. 2011b). In the latter case, judicious gentle corrosion of the chert rock was necessary to expose the <1 μm cells, many of which exhibit cell division and cell lysis.

While the macroscopic textures could be observed in situ on Mars, it is clear that the microscopic textures and the organic geochemical investigations discussed above can only be made in a terrestrial laboratory. Table 2.15 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2E and move toward an assay of possible biosignatures of ancient Martian life.

***Investigation Strategy 2.2F:* Identify any chemical evidence of life.**

The major elements in living organisms are carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus. Some elements, e.g., metals, are present in smaller amounts but have essential roles, while others have no significant roles. Post-burial processes transform biological organic matter to geological residues with

Table 2.15. Samples and measurements implied by Investigation Strategy 2.2E.

Samples identified to advance Investigation Strategy 2.2E:

- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.2E:

- Evaluate mounding and layers for indications of past biological activity. Microbial fabrics and mesoscale biolaminated sedimentary structures (e.g., stromatolites) can persist in rocks even after chemical biosignatures have been lost through oxidation, radiation, or heating.
- Characterize microscale or macroscale rock or mineral fabrics and structures. For example, microbial biofilms can alter the chemistry and physical properties of sediments. Use thin sections and rock chips to search for microscale or macroscale rock, mineral, or carbonaceous fabrics and structures that are consistent with formation or fossilization of biological entities (e.g., microbial biofilms and microbialites), but inconsistent with chemical or abiotic processes.
- Evaluate the possibility of molds or other types of impressions (casts) or associated geochemical signals that may indicate past biological activity or organic matter which may now have vanished, including mineralogically replaced fabrics that may have once been microbially produced.
- Characterize mineral surfaces and interiors to search for physical evidence of metabolic activity (e.g., pits and trails), especially where associated with redox gradients. Such features can indicate the former presence of endolithic microorganisms and communities (e.g., Friedmann 1993; Reid et al. 2000; Foucher et al. 2010). Trace fossils (e.g., movement trails) could indicate microscale dissolution textures due to "mineral mining" by bacteria. Use microscopy to image mineral surfaces and interiors to search for physical evidence of metabolic activity (e.g., pits and trails), especially where associated with redox gradients.
- Undertake hyperspectral analysis of rock sample surfaces to investigate changes in organic carbon content, water content, and mineralogy that may point to biological activity.
- Undertake high-resolution, in situ investigation of textures and structures that may be related to fossilized microbial biofilms, colonies, and cells.

much less nitrogen, oxygen, and eventually, hydrogen (Van Krevelen 1950). The relative abundances of elements can therefore indicate the possible presence or former presence of biological organic matter and can be used to assess postmortem processing steps that degrade any original biological signal. Biological activity can alter the chemical composition of its surroundings as it acquires energy via redox reactions or chemical building blocks by altering inorganic phases. Such patterns can

Table 2.16. Samples and measurements implied by Investigation Strategy 2.2F.

Samples identified to advance Investigation Strategy 2.2F:

- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.2F:

- Fe oxide or Fe sulfide precipitates (e.g., framboids).
- Fe or Mn redox fronts.
- Fractures, vugs, vesicles, or pore space filled with precipitated minerals (carbonates, silica, sulfates, clays, oxides).
- Zones enriched in minerals formed by leaching or in situ transformations.
- Crystallographic structures and major- and minor-elemental abundances of individual phases.
- Abundance patterns of minerals and other phases plus their elemental and chemical compositions.
- Example methods include XRD, XRF, XAS, XCT, Raman spectroscopy, NMR, and TEM.

indicate conditions of formation and alteration and also might provide evidence of chemical equilibria or disequilibria that is inconsistent with abiotic processes and thus might indicate biological activity.

Table 2.16 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.2F and move toward an assay of possible biosignatures of ancient Martian life.

2.3 Sub-Objective 2.3. Assess the Possibility That Any Life Forms Detected Are Still Alive, or Were Recently Alive

ASSAY FOR THE PRESENCE OF BIOSIGNATURES OF PRESENT LIFE	
Why is this objective critical?	*The search for life is one of the driving objectives for Mars exploration in general, and sample studies are an essential component of astrobiology strategy.*
Which are the most important samples?	*All of the samples collected as part of Objective 1 are of interest.*

2.3.1 Introduction and Current State of Knowledge

Ancient Mars was more hospitable to life than it is today. Approximately 3.5 billion years ago, Mars's early atmosphere created warmer wetter conditions, enabling liquid water to flow on the surface (Hurowitz et al. 2017). Today, the Martian environment is less conducive to life. It has a thin atmosphere and temperatures fluctuate wildly, averaging approximately

−60 °C and ranging from −125 °C to 20 °C. Radiation bombards the surface. Because life on Mars is more likely to have existed in the hospitable past than under current conditions, the formal life-related objective of the Mars 2020 sample-collecting rover is to seek signs of extinct life.

Recent discoveries suggest that liquid water may flow on Mars, either on the surface or directly beneath it (McEwen et al. 2011; Martín-Torres et al. 2015; Ojha et al. 2015; Dundas et al. 2017; Orosei et al. 2018; Webster et al. 2018), opening the possibility that life may exist on modern Mars. If life arose on early Mars, it either adapted to the current extreme conditions or went extinct (Ulrich et al. 2012).

To determine whether life is capable of survival and growth on modern Mars, investigations often focus on extremophile isolates or microbial communities in analogous environments such as permafrost. Extremophiles and spore-forming organisms from Earth can survive under simulated Martian conditions or in space (Morozova et al. 2007; Onofri et al. 2015; Mickol and Kral 2017). However, the subset of organisms capable of metabolic activity or replication is much smaller. Chemolithoautotrophs (which harness inorganic substrates for energy, electrons, and biomass) are considered particularly good models for potential Martian life forms because they do not require organic substrate. However, if microbial life exists on Mars, it likely forms interactive community assemblages that transfer energy and biomass among trophic levels. Therefore, heterotrophs that grow under Mars-like conditions may also be appropriate analogs. Though no simulation experiments completely replicate Martian conditions, there is evidence that some of Earth's chemolithoautotrophs (methanogens in particular) (Chastain and Kral 2010; Kral and Altheide 2013; Kral et al. 2016; Sinha et al. 2017) and heterotrophs (Nicholson et al. 2013; Schuerger et al. 2013; De Vera et al. 2014) can metabolize and divide in Mars simulation experiments. For example, in an experiment that simulated pressure (7 mbar), temperature (0 °C), and atmospheric composition (CO_2-enriched), Schuerger and Nicholson (2016) isolated 20 bacterial species in soils originating from extreme oligotrophic environments.

Metabolically active microbial communities exist in some Antarctic permafrost locations (an Earth analog that well reflects conditions on Mars) (Bakermans et al. 2014; Faucher et al. 2017), but not in others (Goordial et al. 2016). The coldest, driest, and most oligotrophic Antarctic permafrost holds evidence of life (DNA), but not metabolic activity (Goordial et al. 2016). Together, these data show that Earth life may grow in a Mars-like environment, but that the conditions are nearing the limits of survivability. However, for life exposed to the Martian environment for eons, it may be able to adapt and evolve, suggesting that life on Mars may be possible.

"Special Regions" are defined as places with sufficient water activity (0.5–1, where 0 is completely dry and 1 is pure water) and temperatures (≥−25 °C) to have the potential to support the reproduction of terrestrial organisms (Rummel et al. 2014; NASEM 2015). Exploration results from Mars to date show that most of Mars is not Special, and have been unable to identify with certainty any place that is Special. However, there are some places for which the data are insufficient to determine whether the environment is Special or not—for the purpose of Planetary Protection, these sites are treated as if they were Special until adequate data can be obtained. If Special Regions exist on Mars, we could speculate that extant Martian life prefers them as a habitat, and therefore that they would be a good place to take samples to seek evidence of indigenous life. However, there are no known Special Regions anywhere on Mars, and no known potential Special Regions within any of the landing sites under consideration for the M-2020 rover. Thus, Special Regions considerations will not apply to the M-2020-prepared sample collection.

2.3.2 Key Open Questions for Sub-Objective 2.3

The probability of discovering extant life at the Martian surface (including by means of MSR) is generally considered to be low. However, its discovery would be so profound that it would shake the pillars of science. It would yield insight into the very fundamentals of life such as what are the basic universal properties of living systems (Goldenfeld et al. 2017) and how life evolves (Table 2.17). Should evidence for recent or extant life be discovered, we outline the following key open questions:

We necessarily base our assumptions about life's universal requirements on our understanding of life on Earth. We think that the most common life forms in the universe and potential life-forms on Mars must (1) be based on carbon, hydrogen, nitrogen, oxygen,

Table 2.17. Key open questions for Sub-Objective 2.3: Assay for the presence of biosignatures of present life.

KEY OPEN QUESTIONS: SUB-OBJECTIVE 2.3
What are life's universal requirements?
Is the path to the emergence of life a universal phenomenon?
How does Martian life conduct the processes we presume are necessary for all life?
Do life on Mars and Earth share a common ancestor?

phosphorus, sulfur, and bioessential metals (C, H, N, O being among the six most common elements in the Universe); (2) require liquid water; (3) use, transport, or store energy; (4) have the ability to organize (e.g., create and maintain a cellular system); (5) regulate and repair its systems; and (6) undergo adaptive evolution (NRC 2007b; Popa 2014). The discovery of life on Mars would allow us to test those assumptions, possibly uncover novel ways in which these processes can be carried out, and identify the commonalities between life on Earth and Mars that may be universally required for the existence of life. It is difficult to overstate the magnitude of the impact such an important discovery would have, which is one of the significant reasons for returning the samples to Earth at substantial public expense.

2.3.3 Why Returned Sample Studies Are Important for Sub-Objective 2.3

In order to investigate samples adequately for evidence of extant or recent life, detection analysis should be based on multiple independent investigative pathways and not limited to a specific feature (Fig. 2.8). We cannot predict with any accuracy life's form and characteristics, whether it would be viable (Fig. 2.9), or whether it shares a common ancestor with life on Earth. No single approach is sufficient for detecting and characterizing life given the potential variables. Thus, to account for these uncertainties, multiple approaches conducted in terrestrial laboratories are key to the successful detection of possible life in a sample. While the rover has limited capacity to house analytical equipment, returned samples can be analyzed in a wide range of Earth's most sophisticated state-of-the-art laboratories. Beyond enabling access to many investigation strategies, returning the samples to Earth would circumvent another hurdle imposed by the limited capacity of a rover—sample handling. Many of the recommended investigation strategies require optimization based on sample physicochemistry and multistep processing requiring close human attention. By way of example, we show the steps in extracting and sequencing DNA, which can change based on salt content, pH, and chemical composition, and requires multiple steps including cell lysis, DNA purification, preparation of DNA for sequencing, and the sequencing itself (Fig. 2.8).

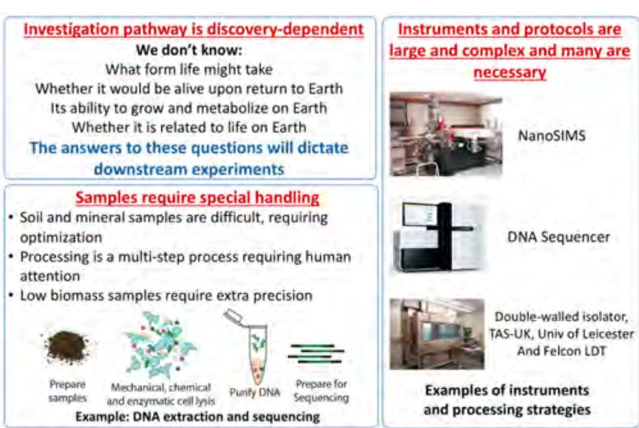

Fig. 2.8. Factors necessitating returned samples to search for evidence of extant life. The search for extant life will only be possible through multiple techniques, most of which are not adaptable to the rover because of involved sample handling requirements and limitations on the size, weight, and complexity of analytical equipment.

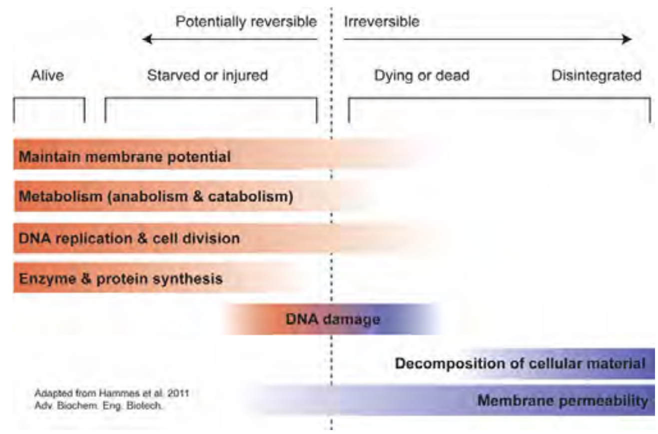

Fig. 2.9. Stages of cell viability and the corresponding cellular processes. In returned samples, life may be found at varying stages of viability. Multiple analysis pathways should be followed so that evidence for life can be detected at any of the stages. Figure adapted from Hammes et al. (2010).

2.3.4 Sample Investigation Strategies to Achieve Sub-Objective 2.3

Life detection analyses should be based on a broad definition for life; not limited by the specific features of life as we know it on Earth. So far, no detailed methods and procedures for the detection of extant extraterrestrial life forms have been defined. A draft protocol for the identification of biohazards in Martian samples was formulated in 2002 (Rummel et al. 2014) and a workshop report about life detection in Martian samples was published in 2014 (Kminek et al. 2014). All investigations rely on several assumptions about the properties we presume to be common to all life. A subset of the investigations will only be successful at detecting Mars life if it shares a common ancestor with Earth life due to travel on meteorites or space debris, whereas other suggested investigations are based on more general characteristics of living entities. Detecting and characterizing life in extreme environments on Earth is a common research goal, so some of the life detection analyses proposed for Mars return samples are modeled on terrestrial methods (Fig. 2.10).

It is important to consider that the amount of material used for destructive life detection should be appropriate to give significance to the results and assurance that life is or is not present. But it would also be necessary to preserve an amount of material for further scientific investigations, so biological assays that require small quantities are highly preferable if the results will be meaningful. Analytical methods are continually improving, increasing in sensitivity, and requiring less input material. Some that currently require sacrificing too much material may be more appropriate in the future. It is difficult to predict the trajectory of methodological improvements, so prioritization should be done based on the state-of-the-art at the time of return rather than on current conditions. Analytical methods for life detection can be divided into those that facilitate a wide survey of a representative portion of different sample types, and those that facilitate a more focused, but high-resolution, examination:

- **Survey methods** are less destructive of samples, and include microscopy, broadband fluorescence, surface scanning and chemistry, tomography, and isotopic measurements. These methods seek structural and basic chemical signatures, and local inhomogeneities.
- **Higher resolution methods** are generally more destructive, and include mass spectroscopic methods, combustion, nucleic acid extraction, isotope analysis, and electron microprobe procedures for elemental mapping. These methods seek to characterize inhomogeneities and more complex structures, and are discussed below in further detail.

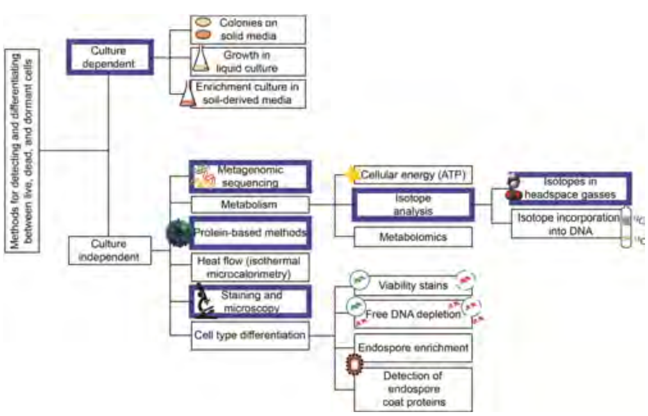

Fig. 2.10. Common methods for detecting and differentiating between live, dead, and dormant cells in terrestrial samples. A subset of investigations recommended for initial investigations into Mars return samples are outlined in bold. Figure adapted from Emerson et al. (2017).

Summarizing, all the cited studies, as well as others of the same type not shown in this report, propose a list of techniques suitable for life detection, and contain extra input into their applications, efficiencies, and limits. Nevertheless, a general, critical approach that compares and ranks the effectiveness of proposed techniques must still be developed.

We have identified four investigation strategies and seven sets of measurements to assess the possibility that any life forms detected are still alive, or were recently alive (Table 2.18).

Investigation Strategy 2.3A: ***As part of developing a complete inventory of the organic molecules present, assess the presence and characteristics of molecules that are diagnostic of organisms that are either alive, or were recently alive.***

Some mission objectives targeting extinct and extant life will overlap because many of the diagnostic biosignatures of ancient life apply to all life. However, there is a subset of these biomarkers that, if discovered, would provide strong evidence for extant (or recent) life. After death, cellular material decomposes into smaller fragments lacking distinctive features—their biological origins become unrecognizable (Westall et al. 2015a). In the search for extinct life, the best organic biomarkers are those that are stable in harsh environmental conditions, such as hopanes, isoprenoids, steranes, porphyrins, straight-chain hydrocarbons, and

Table 2.18. Summary of sample-related investigation strategies to assay for possible extant Martian life.

Investigation Strategies (IS) for Objective 2 Sub-Objective 2.3		
2	**Life**	**Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.**
2.3	Biosignatures —modern	Assess the possibility that any life forms detected are still alive, or were recently alive.
IS 2.3A	As part of developing a complete inventory of the organic molecules present, assess the presence and characteristics of molecules that are diagnostic of organisms that are either alive, or were recently alive.	
IS 2.3B	Assess the possibility of metabolism and respiration.	
IS 2.3C	Assess the possibility that organisms within the sample are capable of reproduction in culture experiments.	
IS 2.3D	Exclude the possibility of contamination with terrestrial life or terrestrial organics as a possible explanation for the data.	

long-chain fatty acids (Martins 2011). In contrast, lower stability molecular markers such as some proteins (e.g., ATP, NAD, phosphoenolpyruvate, cyclic AMP, coenzyme A), chiral amino acids, and nucleic acids (DNA and RNA) are signatures of recent life (Aerts et al. 2014; Röling et al. 2015).

The short-term survivability of nucleic acids means that its detection would be strong evidence of recent life. This investigative avenue is feasible only if life on Mars and Earth share a common origin and thus share DNA/RNA as genetic material. However, should this be the case, DNA/RNA sequencing throws open a window that would enable us to characterize Mars life and its evolutionary history at a detailed level. In the fossil record on Earth, DNA persists on the order of tens of thousands of years (Noonan et al. 2005, 2006) and hundreds of thousands of years (Orlando et al. 2013; Dabney et al. 2013a, 2013b)—a short period on the evolutionary time scale. The ability of fossil DNA to persist over longer time scales depends heavily on environment. DNA preserved for up to ~8 million years has been found in Antarctic ice (Bidle et al. 2007). However, other claims of DNA persisting for over a million years have been met with skepticism and are thought to stem from modern contamination (Vreeland et al. 2000; Graur and Pupko 2001; Penney et al. 2013; Santiago-Rodriguez et al. 2014; Weyrich et al. 2014). The integrity of the nucleic acid molecules (not just the presence or absence) also contains age-related information. Metabolically active cells repair DNA and RNA damage. In the absence of repair machinery that exists in a living cell, damage accumulates and DNA and RNA becomes fragmented (Dabney et al. 2013a, 2013b). Therefore, the extent of the damage (i.e., the size of the fragments) is an indicator of when life existed at a specific sampling location.

If nucleic acids are discovered, one promising method of in-depth characterization is metagenomics, which is the process of isolating and sequencing all DNA directly from an environmental sample. Though metagenomics requires that life shares nucleic acids as a common hereditary molecule, it does not rely on cultivation, nor does it rely on a priori sequence information. Only minute amounts of input DNA are required for metagenomic analysis. Prior to sequencing, DNA is amplified through polymerase chain reaction. This approach can also be used for other genetic material such as RNA. This makes the metagenomics approach attractive for Mars samples, which will likely be low biomass. On Earth, this has been done on low-yield samples from old and/or extreme environments such as Lake Vostok in Antarctica (D'Elia et al. 2008; Knowlton et al. 2013), ancient permafrost (Rivkina et al. 2016; Mackelprang et al. 2017), and ancient hominid remains (Noonan et al. 2005, 2006).

Unless Mars was recently seeded with Earth life, it should be phylogenetically different from modern life, either having diverged from the tree of life prior to the most recent common ancestor to life on Earth or showing a deep-branching evolutionary relationship (Fig. 2.11). On Earth, environmental samples yield many sequences that do not match anything in sequence databases and repositories. These data are collectively referred to as "microbial dark matter." We expect the same phenomenon in Martian DNA/RNA but to a much greater extent. However, there are common features and cellular machinery that all DNA-based life must share. These include ribosomes, DNA/RNA repair enzymes, and transcription/translation machinery. The genes encoding these proteins, enzymes, and RNAs are remarkably well conserved across all domains of life and would be the basis for evaluating the evolutionary history of life on Mars and determining how it is related to life on Earth. Analysis of other DNA sequences may yield insights into the metabolic and physiological functions and strategies. Though we expect that most sequences would be unidentifiable, those that show homology to known sequences would yield important insights.

Table 2.19 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy

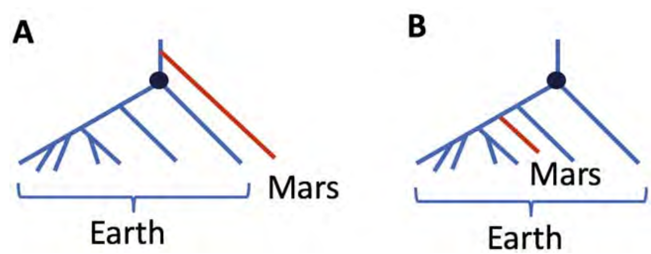

Fig. 2.11. A) Expected evolutionary relationship between life on Mars and Earth in the scenario where they share a common ancestor. B) Expected phylogenetic tree in the case where Mars return samples are contaminated with DNA from Earth organisms.

Table 2.19. Samples and measurements implied by Investigation Strategy 2.3A.

Samples identified to advance Investigation Strategy 2.3A:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.3A:
- Measure the presence of biochemical species, especially pigments, proteins, DNA, RNA, lipids, etc.

2.3A and move toward an assay of possible biosignatures of present Martian life.

Investigation Strategy 2.3B: ***Assess the possibility of metabolism and respiration.***

A primary objective of NASA's *Viking* Mission to Mars was to search for evidence of extant life. Two *Viking* landers carried out a series of biological experiments, including the labeled release experiment, which was designed to detect metabolic activity. In this experiment, simple ^{14}C-labeled substrates, water, and Martian soil were combined and monitored for the evolution of radioactive gases (Levin and Stratt 2016) as evidence that microorganisms had metabolized the substrate. *Viking* instruments detected ^{14}C labeled gas; however, it is widely accepted that those data were due to oxidizing agents in the regolith rather than microbial activity (Lasne et al. 2016).

Despite the controversy surrounding the labeled release experiment and the eventual conclusion that it did not find evidence of life, the rational underpinning of the experiment may be useful in guiding the search for life in the M-2020 returned samples—the idea to search for evidence of active metabolic processes. The orders of magnitude improvements in technology and the availability of sophisticated Earth laboratories would greatly improve sensitivity and allow us to test for metabolic processes beyond the ability to catabolize a handful of simple carbon substrates (a metabolism not likely to exist on the surface of Mars). It would also attenuate the probability of ambiguous and controversial results as seen during the *Viking* mission.

In this investigation, samples would be incubated with "heavy"-isotope-labeled substrate using various combinations of deuterated water, ^{13}C- or ^{15}N-labeled substrates, and other stable isotope-labeled substrates (Trembath-Reichert et al. 2017). The evolution of labeled gases in the headspace would be indicative of Martian life and could yield information about the metabolic processes. An important consideration for this experiment is the potential contamination with Earth life. Unlike the metagenomic analysis described above, there is no clear way to determine if a positive result originates from contaminants. We therefore recommend a series of well-designed controls, and that stringent measures be taken to prevent contamination. We also recommend an attempt at DNA extraction and sequencing of any samples showing evidence of metabolic activity as an assay for contamination (Fig. 2.11).

Table 2.20 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.3B and move toward an assay of possible biosignatures of present Martian life.

Table 2.20. Samples and measurements implied by Investigation Strategy 2.3B.

Samples identified to advance Investigation Strategy 2.3B:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.3B:
- Measure the abundance of isotopes, isotopologues, and isotopomers.
- Extract and sequence DNA.
- Identify and measure evidence for cellular growth, metabolism, and respiration.

Investigation Strategy 2.3C: ***Assess the possibility that organisms within the sample are capable of reproduction in culture experiments.***

Success in cultivating organisms from Martian samples would be the ultimate proof of extant life. On Earth we can only culture a few percent of all environmental microorganisms because it is difficult to predict and reproduce conditions amenable to growth. We expect that Martian organisms would be no less recalcitrant. Therefore, it is critical that growth experiments be conducted under conditions present at the sample site. The *Viking* lander gas-exchange and labeled release experiments were conducted under suboptimal Martian conditions without full consideration of the diversity of microbial physiologies (Schuerger and Clark 2008). As such, it is unclear whether the failure to detect clear signals was due to assay conditions or the absence of life. In the future, experimental design should be based upon (1) chemical analyses of returned samples, (2) Mars surface conditions (temperature, pressure, and atmosphere), and (3) our knowledge about the physiology and metabolism of microorganisms under similar conditions on Earth (Schuerger and Clark 2008).

Table 2.21 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.3C and move toward an assay of possible biosignatures of present Martian life.

Table 2.21. Samples and measurements implied by Investigation Strategy 2.3C.

Samples identified to advance Investigation Strategy 2.3C:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.3C:
- Measure cell size, shape, and structure.
- Evaluate morphological indications of replication and specialized features like motility structures.

***Investigation Strategy 2.3D:* Exclude the possibility of contamination with terrestrial life or terrestrial organics as a possible explanation for the data.**

A crucial component in assessing returned samples for evidence of extant life is to exclude the possibility of contamination with terrestrial life or terrestrial organics as a possible explanation for the data (Bass and Beaty 2011). The issue of contamination is addressed in other sections, so we limit our discussion to topics relevant to the search for extant life. If indigenous modern life exists in Martian samples, it will likely be present at low abundance similar to extreme environments on Earth. Thus, we will need to prepare for the return samples to be low biomass, which are particularly sensitive to contamination. This means not only taking proper cleanliness precautions in the terrestrial laboratories to prevent contamination during sample preparation and analysis but also employ a very strict organic contamination protocol on the development of the rover and all its parts (e.g., ten Kate et al. 2008). To remove or minimize contamination, tests and analyses should be performed periodically on clean rooms and all subsystems that would be in contact or in proximity of collected samples. Tests have to assess the presence and abundance of:

- *Inorganic compounds:* ferromagnesian silicates, aluminosilicates, Fe and Cr oxides, phosphates, metals, sulfides, carbides, nitrides, and hydrated silicates (e.g., clays).
- *Organic compounds:* DNA, soluble carbonaceous and insoluble kerogenous-like compounds, graphite, aliphatic and aromatic hydrocarbons, heterocyclic compounds, amines and amides, alcohols, carbohydrates, biomolecules, and possibly, simple life forms.

To draw meaningful conclusions regarding the possibility of extant Martian life, scientific investigations must have sufficient resources to rule out contamination. We assume that biological contamination will be detected in the spacecraft, receiving facilities, and returned samples. To appropriately interpret evidence for Mars life in returned samples, we must be able to distinguish between terrestrial contaminates and indigenous Martian life. For this reason, a genetic inventory of both the spacecraft and sample processing/analysis facilities is critical (RSSB et al. 2018a). A genetic inventory represents an important part of the background information related to detection of genetic material in Mars spacecraft and returned samples. If DNA or RNA detected in returned samples is closely related to life on Earth, it would likely be the result of contamination rather than evidence of Martian life (Fig. 2.11).

Table 2.22 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 2.3D and move toward an assay of possible biosignatures of present Martian life.

Table 2.22. Samples and measurements implied by Investigation Strategy 2.3D.

Samples identified to advance Investigation Strategy 2.3D:
- All samples collected as a part of Objective 1 are of interest.

Measurements identified to advance Investigation Strategy 2.3D:
- Measure expected contamination levels and calculate their subsequent transfer on returned samples.

3 OBJECTIVE 3: QUANTITATIVELY DETERMINE THE EVOLUTIONARY TIMELINE OF MARS

DETERMINE THE EVOLUTIONARY TIMELINE OF MARS	
Why is this objective critical?	*Quantitative comparison of the histories of Earth, Mars, and the Moon is a key input to understanding the origin and evolution of the inner solar system, including the history of habitability.*
Which are the most important samples?	*Most/all of the samples collected as part of Objective 1 are of interest, including clastic or chemical sedimentary rocks, igneous rocks, and impact breccias.*

3.1 Introduction and Current State of Knowledge

Meteoritic evidence indicates that Mars accreted in the first 2–10 Ma after the formation of the first solids in the solar system (Dauphas and Pourmand 2011; Kruijer et al. 2017) from material with an O-Ti-Cr-Ni isotopic provenance more similar to ordinary chondrites than carbonaceous chondrites and distinct from the Earth–Moon system (Warren 2011). It likely formed a deep, global magma ocean within ~30 Ma after solar system formation (Debaille et al. 2009; Borg et al. 2016; Kruijer et al. 2017), from which the Martian core last equilibrated with its mantle at pressures of ~14 GPa (Righter and Chabot 2011). After core formation, Mars likely accreted a late veneer that was less extensive than that inferred for the Earth's mantle, but from a similar provenance (Brandon et al. 2012). The formation of most of the mass of the Martian crust is constrained to have occurred by 4.43 Ga (Humayun et al. 2013; McCubbin et al. 2016a; Bouvier et al. 2018), and the mantle appears to have formed a series of isotopically

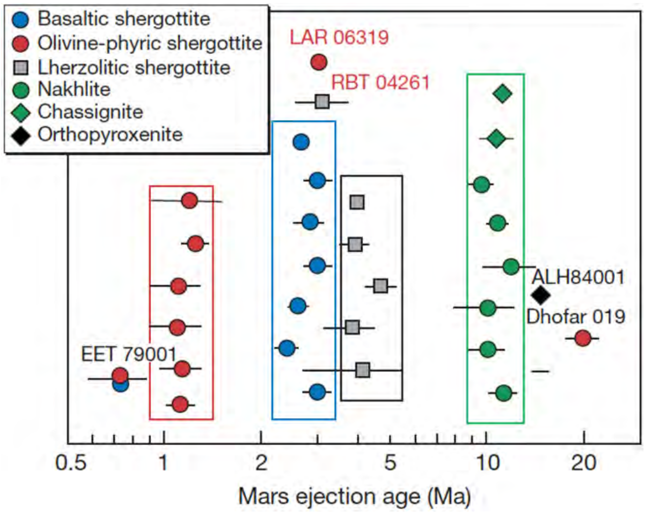

Fig. 3.1. Mars ejection ages of the different petrologic types of known Martian meteorites; the names of only those meteorites that do not fall within the ejection age clusters (boxes outlined in different colors) are given here (from McSween 2008).

distinct reservoirs from which subsequent magmas were derived with little mixing (Debaille et al. 2007). These inferences about Mars's earliest differentiation are based on the assumption that Martian meteorites provide a representative sampling of the Martian mantle and crust. However, since the known Martian meteorites have ejection ages that mostly fall within a few main clusters (Fig. 3.1), this assumption almost certainly is not valid. It is more likely that the Martian meteorites were derived from only a few ejection sites (McSween and McLennan 2014).

The earliest phase of Martian magmatism (>4.35 Ga) has been largely overprinted by impact melting in breccias, but four distinct episodes of igneous activity are known at ~4.1 Ga (Cassata et al. 2010; Lapen et al. 2010), ~2.4 Ga (Herd et al. 2017; Lapen et al. 2017), ~1.4 Ga (Cohen et al. 2017), and between 0.15 and 0.60 Ga (Nyquist et al. 2001; Moser et al. 2013). Remnant magnetization in Martian meteorite ALH 84001 demonstrates a dynamo had initiated on Mars at or before 4.1 Ga (Weiss et al. 2008). Orbital evidence indicates that large parts of the highlands formed early in Martian history with subsequent abundant volcanic resurfacing during the Hesperian (3.7 Ga to ~3.0 Ga). Volcanic activity was localized at the large volcanic provinces (Tharsis, Elysium, and west of Hellas basin) (Werner 2009), none of which is firmly linked to, and thus sampled by, the meteorite collection. Calibrating the chronology of igneous activity for Mars will create a temporal frame for the interpretation of both interior (core, mantle) and exterior (atmosphere, cryosphere, and hydrosphere) dynamics of Mars.

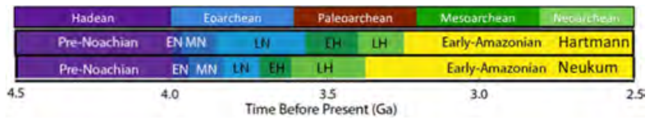

Fig. 3.2. Comparison of the two separate Martian crater chronologies that are widely used: (1) Hartmann (Hartmann 2005) and (2) Neukum (Hartmann and Neukum 2001; Ivanov 2001), with the chronology of early Earth (which is calibrated by radioisotope ages) (modified from Ehlmann et al. 2016).

This objective seeks to provide radioisotope-based chronological constraints for major evolutionary events on Mars. This includes the timing of Mars's accretion and differentiation; the timing of magmatic, tectonic, magnetic, fluvial, and impact events; and the timing of formation of major deposits of secondary minerals and geomorphologic features. Absolute ages of geological processes will enable a better understanding of the geological evolution of Mars and facilitate a comparison with equivalent processes on Earth. The record from Mars is important because it corresponds to Earth's early (Hadean-Archean) history for which only little of the geologic record is preserved (Fig. 3.2). The highest priority questions relating to the chronology of processes and events on Mars that remain to be answered, as well as the investigation strategies and samples to address these, are set out below in more detail.

3.2 Key Open Questions for Objective 3

To a certain extent, geochronology overlaps with all of the other scientific objectives in this report. We want to know not only how and why various geologic processes operated on Mars but also when (Table 3.1). Thus, there is an important link between geochronology and our Objective 5 (which relates to planetary-scale

Table 3.1. Key open questions for Objective 3: Constraining the evolutionary timeline of Mars.

KEY OPEN QUESTIONS: OBJECTIVE 3
How does the impact flux on Mars compare to that on the Moon, and was there a period of late heavy bombardment on Mars?
When did Mars's early dynamo shut down?
What were the accretionary building blocks of Mars, and how long did the processes of crust formation and metal-silicate segregation (core formation) take?
What was the duration of igneous activity on the surface of Mars?
What are the time scales of aqueous, hydrothermal, and sedimentary processes (including rates of burial, uplift, and erosion of surfaces) on Mars?

processes), an additional link to Objective 2 (when were environmental conditions in the habitable window), an additional link to the specific geologic processes described in Objective 1 (e.g., when did hydrothermal activity take place?), and further connections to Objective 4 relating to when the volatile reservoirs formed and were modified. However, quantitative isotope geochronology is so important to Mars science in general that we felt it had to be called out separately. Within the general subject area of geochronology, the subject matter experts within iMOST were able to decompose it into seven discrete investigation strategies (Table 3.2), which are listed in approximate priority order. These strategies have different implications for samples desired, and for the measurements that would be done on those samples.

The following are some fundamental open questions relating to Mars which would be addressed through careful analyses of appropriate returned samples in Earth-based laboratories.

3.3 Why Returned Sample Studies Are Important for Objective 3

Our current understanding of the time scales of Martian geological processes is hampered by the fact that no unambiguous links between well-dated meteorites and Martian surfaces (e.g., by association with known craters) have been made and in situ ages at Gale Crater have large uncertainties (±350 Ma). Therefore, MSR is essential to achieve high-precision, high-accuracy dates for samples from known sites that would provide crucial information for understanding the chronology of processes on the surface and in the interior of Mars. In particular, the specific open questions noted above can only be addressed with the level of precision (a few to 10s of Ma) and accuracy that can be achieved through state-of-the-art radiogenic isotope analyses on well-characterized samples in Earth-based laboratories. Importantly, some chronometers are disturbed by alteration and metamorphism associated with impact on the Martian surface, so that the reliability of individual age determinations can only be confirmed by analyses in Earth-based laboratories where concordant ages from multiple isotopic systems can be obtained for the same rock. Furthermore, in any given sample, ages determined for different components within a rock type can provide the timing of distinct events. For example, an impact breccia may contain clasts that represent igneous or sedimentary lithologies or impact melts. Remote in situ analyses of such a rock type on Mars would yield an "age" that could be meaningless given that the different lithologies and clasts may represent separate events occurring at very different times in Martian history. Also,

Fig. 3.3. For state-of-the-art high-precision radioisotope analyses, sample handling and chemical processing in a clean laboratory such as the one shown here are typically required. Image credit: Center for Meteorite Studies at Arizona State University.

it is important to note that ages determined on Martian meteorites using whole rock isochron techniques do not constrain the formation age of the samples, but instead reflect mixing processes that often have little chronologic significance.

To date a specific event that is recorded within particular components of a rock, it is important to characterize that sample and its components using microbeam techniques (such as scanning and transmission electron microscopy and electron probe microanalysis). Following this characterization, it is typically necessary to separate individual phases prior to further processing involving chemical separation of elements under ultraclean laboratory conditions for high-precision isotope analyses. For the foreseeable future, such complex sample characterization and processing can only be performed by humans in Earth-based laboratories equipped with state-of-art facilities and instrumentation (Fig. 3.3). Given this, it would be important to return Martian samples to Earth for the chronological investigations necessary to address the open questions noted above. Finally, measurement precision and techniques are continuously being improved, and these technological and analytical advances often open up completely new and unforeseen avenues of research and methods of investigation. Thus, the full potential in terms of information to be gained from sample analyses can only be realized on returned Martian samples.

Table 3.2. Summary of sample-related investigation strategies to constrain and quantify the evolutionary timeline of Mars.

Investigation Strategies (IS) for Objective 3		
3	**Geochronology**	**Quantitatively determine the evolutionary timeline of Mars**
IS 3A	Calibrate the cratering chronology method by determining the radioisotope age for the formation of one or more geologic surfaces which has a well-defined cratering density.	
IS 3B	Assess the existence of a late heavy bombardment on Mars, for comparison to the impact bombardment history of the Moon.	
IS 3C	Quantify the thermal/magnetic history of Mars in order to test the present model of Martian mantle convection, in particular the possible early existence of plate tectonics versus stagnant lid convection, and the dynamo history (including the timing of magnetic field cessation), and their relationships to other major changes in Martian geologic history, particularly atmospheric escape.	
IS 3D	Determine the age of specific events associated with the Martian hydrosphere, such as sedimentation, hydrothermal activity, activity associated with deep groundwater, subaerial weathering, and associated possible transitions in habitability.	
IS 3E	Improve our understanding of the timeline, building blocks, and geochemical reservoirs involved in the accretion and early differentiation of Mars.	
IS 3F	Determine the history of surface exposure, including the timing and rates of crustal uplift/erosion and burial on Mars.	
IS 3G	Constrain long-duration near-surface temperatures using radiogenic and cosmogenic noble gas thermochronology.	

3.4 Sample Investigation Strategies to Achieve Objective 3

We have identified seven investigation strategies and 13 associated sets of measurements to allow quantitative determination of the evolutionary timeline of Mars (Table 3.2).

Investigation Strategy 3A: ***Calibrate the cratering chronology method by determining the radioisotope age for the formation of one or more geologic surfaces that has a well-defined cratering density.***

The cratering chronology method has proven to be extremely useful for interpreting the relative ages of planetary surfaces and has the advantage that it can be applied based on observations from orbit. However, the absolute calibration of the cratering rate has thus far only been possible for the Moon. In fact, all planetary cratering chronology models, including that for Mars, are calibrated against the lunar cratering record established from Apollo and Luna samples (Hartmann and Neukum 2001; Ivanov 2001; Hartmann 2005; Werner et al. 2014). In applying the lunar calibration to Mars, it is recognized that there are errors associated with the fact that the projectile flux at Mars may not be identical to that at the Moon. There is also additional uncertainty given that the earliest lunar bombardment history is still poorly understood for the time period between 4.2 and 3.9 Ga (e.g., Morbidelli et al. 2018). Specifically, it is still unclear whether the crater-forming projectile flux was monotonically declining or if (late) giant planet migration caused one or more peaks in the flux. Application of chronology models based on the lunar cratering record to Mars potentially introduces uncertainties of hundreds of millions of years (Fig. 3.2).

The first ever in situ age determination on an extraterrestrial body, a 4.21 ± 0.35 Ga age for Noachian–Early Hesperian materials in a mudstone at Gale Crater (Farley et al. 2014), unfortunately has uncertainties that are too large to make a confident calibration of the Martian cratering chronology. These facts strongly argue for MSR to provide precise and accurate sample age determinations for calibrating its cratering record. Such investigations would also provide fundamental insights into the timeline for the terrestrial planet formation processes of accretion and differentiation, and subsequent evolution of the interior and surface of Mars through geologic time.

Chronologic studies of well-characterized and carefully selected Martian surface materials are needed to address the important question of whether or not the lunar cratering record can be used for calibration of surface ages on all terrestrial planets. MSR is required for dating individual craters because there is the possibility of later disturbance by hydrothermal activity, as seen in the meteoritic regolith breccia NWA 7034 (McCubbin et al. 2016a). Single-grain U-Pb ages of zircon and monazite have retained the formation time of large, ancient terrestrial impact craters despite a younger hydrothermal history (Moser 1997). High-temperature impact melts in large, deeply eroded Martian craters (e.g., basin fill unit exposed in Jezero crater) could potentially be used to constrain the timing of their formation. For the best age resolution, calibration of the cratering rate on >3.5 Ga and <1 Ga Martian terrains is the highest priority because cratering statistics during this period have been well established (Table 3.3).

Table 3.3. Samples and measurements implied by Investigation Strategy 3A.

Samples identified to advance Investigation Strategy 3A:

- Igneous samples from an extensive lava flow in the >3.5 Ga and <1 Ga age ranges from surfaces for which well-determined cratering statistics have been well established.
- Samples, including impact melts, taken from individual craters.
- Breccias associated with large basin-forming impacts.

Measurements identified to advance Investigation Strategy 3A:

- ^{40}Ar-^{39}Ar measurements.
- U-Pb measurements, especially of zircons or monazites.

Investigation Strategy 3B: ***Assess the existence of a late heavy bombardment on Mars, for comparison to the impact bombardment history of the Moon.***

A late heavy bombardment (cataclysm) on the terrestrial planets would be manifest by an overabundance of impact craters at a single period in time. The cataclysm hypothesis envisions an intense spike in the bombardment rate at ~3.8–4.1 Ga, perhaps triggered by the orbital migration of the outer planets (Levison et al. 2001; Gomes et al. 2005; Morbidelli 2010). On the other hand, the accretionary tailing hypothesis maintains that impact rates gradually declined, in which a decaying impactor flux would be a natural result of a slowly depleting source region. The debate has not been resolved with returned lunar samples because the Apollo and Luna sampling sites were all located on the near side of the Moon, in a small area dominated by several large impact basins: Imbrium, Nectaris, and Serenitatis, so that biased sampling of these basins might have skewed the age distributions. Therefore, new information from Mars could establish whether there was a monotonic decay of the bombardment flux or whether orbital rearrangements of the giant planets caused flux variations during this period.

Post-accretion meteoritic bombardment of Mars is evident from the heavily cratered southern highlands. There are virtually no intact geological formations dating to this period (Hadean) on Earth, so our knowledge of the bombardment chronology comes from dating lunar breccias and impact melt glasses (Tera et al. 1974; Cohen et al. 2000; Nemchin et al. 2012). The two competing hypotheses for the bombardment rate involve distinct scenarios for the pre-3.8 Ga impact history of planets with important ramifications for early life (Abramov and Mojzsis 2009). From a biosphere point of view, bombardment of basin-forming projectiles can be seen as a series of "planet-sterilizing" (Sleep et al. 1989) events, with implications for when Mars started the "habitability clock" and the initial reference conditions for reconstructions of potential paleobiology, atmosphere, hydrosphere, and interior evolution.

The ages available from in situ missions (4.21 ± 0.35 Ga; Farley et al. 2014) and from meteorites (4.43–4.35 Ga zircons in NWA 7034/7533 and 4.09 ± 0.03 Ga for ALH 84001; Lapen et al. 2010; Humayun et al. 2013; McCubbin et al. 2016a) have provided mixed support for the Late Heavy Bombardment on Mars. Returned samples from Mars should help evaluate the validity of a solar system-wide late heavy bombardment hypothesis. On one hand, if the impact resetting ages of samples of multiple geologic age yield a significant range, a monotonic decrease in impactor flux rate might be inferred. On the other hand, Late Heavy Bombardment would be supported if numerous resetting ages of ~3.8–4.1 Ga were obtained.

While it has been demonstrated that the timing of Martian igneous and shock events can be preserved in mineral grains down to the scale of microns (e.g., Moser et al. 2013; Humayun et al. 2013), shock metamorphic effects and isotopic resetting within rocks and impactites are often spatially heterogeneous. Therefore, a sample site/unit with very well-characterized primary textures will, regardless of dating method, be necessary to accurately infer the age of a large cratering event or cratered surface from the geochronology of microscopic minerals. Such a sample would also serve multiple other iMOST objectives and investigation strategies (e.g., Objective 1.5, igneous history) (Table 3.4).

Investigation Strategy 3C: ***Quantify the thermal/magnetic history of Mars in order to test the present model of Martian mantle convection, in particular the possible early existence of plate tectonics versus stagnant lid convection, and the dynamo history (including the timing of magnetic field cessation), and their relationships to other major changes in Martian geologic history, particularly atmospheric escape.***

Martian surface lithologies are iron-rich and strongly magnetized, likely dating back to the Noachian epoch when the surface may have been habitable. Paleomagnetic measurements of returned samples could transform our understanding of the

Table 3.4. Samples and measurements implied by Investigation Strategy 3B.

Samples identified to advance Investigation Strategy 3B:

- A sample suite with well-characterized primary textures.

Measurements identified to advance Investigation Strategy 3B:

- Isotopic age dating (^{40}Ar-^{39}Ar and U-Pb).

Table 3.5. Samples and measurements implied by Investigation Strategy 3C.

Samples identified to advance Investigation Strategy 3C:
- Igneous rocks with well-constrained ages, ideally with known orientation.
- Time sequences of oriented in situ igneous rocks.

Measurements identified to advance Investigation Strategy 3C:
- Coupled magnetic and geochronologic measurements.
- Magnetic paleointensities and orientations.

Table 3.6. Samples and measurements implied by Investigation Strategy 3D.

Samples identified to advance Investigation Strategy 3D:
- Unaltered sedimentary rocks.
- Sedimentary and igneous rocks displaying signs of secondary hydrologic activity.

Measurements identified to advance Investigation Strategy 3D:
- Oxygen isotopic composition, REE in phosphates, Li isotopes.
- Appropriate dating analyses for each sample (e.g., REE in phosphates, Li isotopes, U-Pb, Re-Os, K-Ar, ^{40}Ar-^{39}Ar, or Rb-Sr methods).

Martian dynamo and its connection to climatic and planetary thermal evolution and provide powerful constraints on the potential preservation state of biosignatures in the samples. Although Mars presently does not have a core dynamo magnetic field, the discoveries of intense magnetic anomalies in the ancient southern cratered terrain by the Mars Global Surveyor mission (Acuña et al. 2008) and remnant magnetization in Martian meteorite ALH84001 (Weiss et al. 2004, 2008) provide strong evidence of a Martian dynamo during the Noachian epoch. The timing of origin and subsequent decline of the field are poorly constrained but have critical implications for planetary thermal and tectonic history (Stevenson 2001) as well as the evolution of the Martian atmosphere and climate (Jakosky and Phillips 2001). Coupled magnetic and geochronologic measurements on a suite of samples spanning the lifetime of the Martian dynamo could establish when the dynamo was active and ceased. Furthermore, time sequences of paleodirectional measurements of oriented samples could constrain the rates of polar wander. To address these issues, samples of in situ igneous rocks for which magnetic paleointensities are to be obtained and amenable to radioisotopic dating are required. Ideally, these samples would be oriented so that polar wander rates can be constrained. However, unoriented samples could still be used to constrain the lifetime and intensity of the dynamo (Table 3.5).

Investigation Strategy 3D: ***Determine the age of specific events associated with the Martian hydrosphere, such as sedimentation, hydrothermal activity, activity associated with deep groundwater, subaerial weathering, and associated/possible transitions in habitability.***

Geologic processes involving water produce a variety of sedimentary rocks that can be dated using a variety of analytical techniques. Age determinations on these materials place constraints on the timing of sedimentation, hydrothermal activity, and subaerial weathering in hydrous environments. Age distributions for rounded, abraded (detrital) grains from sediment place a maximum age of sediment deposition. Low-temperature overgrowths on sedimentary grains rims can be used to date low-temperature secondary alteration from the action of fluids in upper crustal deposits. This determines the timing of water/rock interaction processes (hydrothermal alteration, acid-sulfate alteration, diagenesis, weathering, aqueous precipitation). Secondary carbonate minerals in cements and fractures can also be dated by the U-Pb method with reasonable precision by LA-ICP-MS (e.g., Hansman et al. 2018). Hydrothermal sulfides and Fe-Mn oxyhydroxides could be dated by Re-Os ages or by Pb model ages. Diagenetic or hydrothermal clays and K-bearing sulfates could be dated by K-Ar (^{40}Ar-^{39}Ar) or Rb-Sr methods.

In addition, there now exist robust, stable isotope signatures (e.g., oxygen isotopes) that indicate the presence of liquid water in the Martian rock cycle. These signatures are preserved for billions of years in silicate minerals, particularly the refractory minerals such as zircon and baddeleyite, both of which can be analyzed using high-precision ion microprobe techniques (e.g., Nemchin et al. 2014; Davies et al. 2018). Application of ion beam techniques that measure both the oxygen isotopic compositions and U-Pb systematics of these refractory minerals can identify times at which water was present in the crustal system. Li isotopes in zircon are likewise valuable indicators of cumulative aqueous weathering in the rock cycle (Ushikubo et al. 2008). All these approaches can be applied to the same sample in order to understand the history of surface and underground water on Mars (Table 3.6).

Investigation Strategy 3E: ***Improve our understanding of the timeline, building blocks, and geochemical reservoirs involved in the accretion and early differentiation of Mars.***

It has been demonstrated that not all solar system materials are derived from the same proportions of nucleosynthetic sources (e.g., Burkhardt et al. 2016). This challenges the premise that the isotopic compositions of primitive meteorites are a perfect proxy for the composition of bulk planets. For an early formed body like Mars, and given the likelihood of the lack of efficient mixing and homogenization of the Martian mantle, nucleosynthetic isotope variations ("anomalies") may exist within its crustal and mantle reservoirs. Such nucleosynthetic anomalies would serve as genetic tracers for the compositions of the building blocks that accreted to form this planet. In this context, it is important to note that the known Martian meteorites do not record nucleosynthetic isotope variations at the level of precision currently achievable by state-of-the-art analytical techniques. However, as discussed earlier, the Martian meteorites are unlikely to be a representative suite of samples of the Martian crust and the lack of such variations in the Martian meteorite record may simply reflect sampling of a limited number of ejection sites (Fig. 3.1). Thus, returned Martian samples would be key to assessing whether nucleosynthetic isotope heterogeneity exists within Mars. In order to better understand the building blocks of Mars, and the variation of nucleosynthetic sources contributing to terrestrial planet formation, stable isotope measurements of returned Martian samples are required. These data could be obtained from the same samples being used for geochronology of igneous rocks as collateral benefits. In addition, similar data could be sought from Martian clastic sediments (which are not represented among the known Martian meteorites).

Although Mars is thought to have differentiated early (e.g., Shih et al. 1982; Harper et al. 1995; Kleine et al. 2002; Borg et al. 2016; Kruijer et al. 2017), the exact age of differentiation is still debated. This debate stems largely from the fact that different isotopic systems yield different ages. Specifically, ages of differentiation based on the isotopic systematics of the basaltic shergottites range from 4.50 Ga (Sm-Nd system) to 4.54 Ga (Hf-W system). To complicate the issue, the nakhlite meteorites do not demonstrate the same isotopic systematics as the shergottites, and appear to have experienced a more complicated geologic history. This makes the significance of the differentiation age based on shergottites difficult to extrapolate to a global geologic system. For example, the isotopic equilibrium observed in the shergottites might indicate that their whole rock isochron age records the time of solidification of a global magma ocean. Alternatively, the lack of equilibrium between the shergottites and nakhlites could be interpreted to indicate that the differentiation age determined from the shergottites only reflects localized equilibrium of a relatively small portion of the mantle.

To address these issues, samples from a wide range of geographic locations are needed. If the whole rocks of mantle-derived samples fall on a single coherent isochron, then equilibrium of these isotopic systems probably existed on a global scale. On the other hand, if various mantle lithologies are not in isotopic equilibrium, then either the existing ages do not record differentiation, or secondary processes occurring in the mantle obscured the chronology. By examining a suite of mantle-derived samples, the age at which Mars differentiated into a core, mantle, and crust can be determined.

Table 3.7. Samples and measurements implied by Investigation Strategy 3E.

Samples identified to advance Investigation Strategy 3E:

- Igneous or clastic sedimentary rocks from a wide range of geographic locations.

Measurements identified to advance Investigation Strategy 3E:

- ^{182}W-^{142}Nd measurements.
- Hf-W measurements.

Due to its short half-life, the Hf-W system in particular could be used to date formation of the earliest Martian crust (Kruijer et al. 2017). Although the ^{182}W and ^{142}Nd systematics of Martian meteorites suggest that Mars's differentiation commenced within the first 30 Ma of solar system history, this conclusion is based on the likely invalid assumption that Martian meteorites provide representative sampling of Mars's geochemical reservoirs. As such, the ^{182}W-^{142}Nd systematics of any returned Martian sample would provide a key test for current models of Mars's earliest differentiation and the subsequent evolution of the Martian mantle (Table 3.7).

***Investigation Strategy 3F*: Determine the history of surface exposure, including the timing and rates of crustal uplift/erosion and burial on Mars.**

Oxidation of organics by exposure of sedimentary rocks at the Martian surface to cosmic radiation for >300 Ma has been raised as a serious concern for the preservation of organic matter (Pavlov et al. 2012). Thus, an important aspect of sampling for possible organics in Martian sedimentary rocks is the selection of the most recently exposed rocks near cliff faces, around impact craters, or where erosion rates have been high. To limit the effects of oxidation and ionizing radiation, the sampling of impact-excavated rock for Martian organic geochemical studies has been proposed (Montgomery et al. 2016). Measurement of the isotopic compositions of nuclides with high neutron capture cross sections (e.g., B, Cd, Sm, Gd) in soil, regolith, and other rocks, would help elucidate the exposure histories of materials in the upper few meters of the Martian surface and constrain the neutron fluences experienced by the rock units (e.g., Russ et al. 1972; Hidaka et al. 2009). On cooling at the surface, material excavated from depth would lock in the ^{4}He formed by alpha decay allowing U-Th-He dating of U-Th-rich accessory minerals (apatite, zircon, etc.). This could constrain the residence times of ejecta. Erosion rates and exposure histories could also be obtained by cosmogenic nuclide (^{3}He, ^{21}Ne, ^{10}Be, ^{26}Al, ^{36}Cl) dating of surface rocks.

In addition to assessing the organic preservation potential of sedimentary rocks, erosion, and sediment production rates, studies of cosmogenic nuclides is beneficial for interpreting isotopic anomalies and geochronology data. For age and source composition determinations, Sm-Nd (e.g., Borg et al. 2016) and Hf-W (Leya and Masarik 2013) chronometers may require corrections for cosmogenic neutron capture on the nuclides of interest.

Rock samples needed for this work would include all returned Mars samples, including clastic or chemical sedimentary rocks recovered for biomarker analysis, igneous rocks, impact breccias, etc. Cores that retained stratigraphy would prove useful for evaluating erosion rates from cosmogenic nuclide abundances measured as a function of depth (Table 3.8).

***Investigation Strategy 3G*: Constrain long-duration near surface temperatures using radiogenic and cosmogenic noble gas thermochronology.**

Obtaining quantitative constraints on near-surface thermal conditions on Mars is important for a variety of questions on Mars, including feasibility and potential duration of liquid water stability, potential magmatic/geothermal activity, impact history, paleomagnetic records, and landscape evolution. Applications of both radiogenic and cosmogenic noble gas thermochronology can provide quantitative constraints on permissible thermal conditions over the last 10^{6} to 10^{9} years on planetary surfaces (Shuster and Weiss 2005; Tremblay et al. 2014; Shuster and Cassata 2015). Although the open-system behavior of radiogenic ^{40}Ar observed in Martian meteorites has been used to place long-duration

Table 3.8. Samples and measurements implied by Investigation Strategy 3F.

Samples identified to advance Investigation Strategy 3F:

- All returned Mars samples, including clastic or chemical sedimentary rocks, igneous rocks, and impact breccias.
- Cores that retained stratigraphy would prove useful for evaluating erosion rates from cosmogenic nuclide abundances measured as a function of depth.

Measurements identified to advance Investigation Strategy 3F:

- Sm-Nd dating.
- Hf-W dating.
- Cosmogenic nuclide (^{3}He, ^{21}Ne, ^{10}Be, ^{26}Al, ^{36}Cl) dating of surface rocks.
- Isotopic compositions of nuclides with high neutron capture cross sections (e.g., B, Cd, Sm, Gd) in soil, regolith, and other rocks.
- U-Th-He dating of U-Th-rich accessory minerals.

Table 3.9. Samples and measurements implied by Investigation Strategy 3G.

Samples identified to advance Investigation Strategy 3G:

- All collected samples are of interest.

Measurements identified to advance Investigation Strategy 3G:

- ^{40}Ar/^{39}Ar and ^{4}He/^{3}He thermochronology, as well as cosmogenic ^{38}Ar, ^{21,22}Ne, and ^{3}He.

thermal constraints on the Martian surface (Shuster and Weiss 2005; Cassata et al. 2010), significant uncertainties result from elevated temperatures associated with ejection from Mars, and transit and atmospheric entry to Earth. In addition, meteorites are not amenable to the use of cosmogenic noble gas thermochronometry due to their exposure during transit to Earth. The returned samples would provide an opportunity to use both radiogenic and cosmogenic noble gas thermochronology (as has been done on returned lunar samples; Shuster and Cassata 2015; Tikoo et al. 2017) to place thermal constraints over time scale that spans from rock crystallization to today, and during most recent time when the collected samples were exposed to cosmic ray interactions in the uppermost few meters of the Martian surface. Depending on their specific lithology and mineralogy, the returned samples would be amenable to ^{40}Ar/^{39}Ar and ^{4}He/^{3}He thermochronology, as well as the use of open-system behavior of cosmogenic ^{38}Ar, ^{21,22}Ne, and ^{3}He. A major advantage of these approaches is that laboratory observations of returned samples provide sample-specific temperature sensitivity, via quantification of noble gas diffusion kinetics (e.g., Shuster and Cassata 2015) (Table 3.9).

4 OBJECTIVE 4: CONSTRAIN THE INVENTORY OF MARTIAN VOLATILES AS A FUNCTION OF GEOLOGIC TIME AND DETERMINE THE WAYS IN WHICH THESE VOLATILES HAVE INTERACTED WITH MARS AS A GEOLOGIC SYSTEM

MARTIAN VOLATILES: INVENTORY, HISTORY, AND INTERACTIONS	
Why is this objective critical?	*Understanding Martian volatiles is essential both to astrobiology strategy and to the evolution of Mars as a planetary object.*
Which are the most important samples?	*Atmospheric gas sample(s); rocks with minerals recording volatiles including hydrous silicates, carbonates, sulfates, nitrates, and chlorides; samples with fluid inclusions.*

4.1 Introduction and Current State of Knowledge

Volatiles have clearly played a key role in the evolution of Mars's atmosphere, hydrosphere, and geosphere, with effects ranging from the geomorphological evidence for outflow channels and valley networks early in Mars's history to formation of alteration products in rocks (e.g., Treiman 2005; Bibring et al. 2006; Ehlmann et al. 2011a; Vaniman et al. 2014; Melwani Daswani et al. 2016) to the current seasonal changes in the polar caps. The atmosphere of Mars was measured for the first time by the *Viking* lander (Chamberlain et al. 1976; Hess et al. 1977). State-of-the-art instrumentation on the *Phoenix* (Niles et al. 2010) and *Curiosity* (Atreya et al. 2013; Mahaffy et al. 2013, 2015; Webster et al. 2013, 2015; Wong et al. 2013; Franz et al. 2015; Conrad et al. 2016) missions have furthered our understanding of the origin of some volatiles, and orbiters such as Mars *Odyssey* have measured global distributions of some, with regional spatial resolution (Boynton et al. 2002; Keller et al. 2006). Recently, the MAVEN mission has been measuring current atmospheric loss rates and processes (Jakosky et al. 2015).

In addition, Martian meteorites have added important evidence on the noble gas content of Mars—ranging from the similarity of the trapped gases, especially the heavy noble gases, in the shergottitic glasses with unfractionated Martian atmosphere as measured by *Viking* (and now also *Curiosity*), to fractionated Martian atmosphere in the nakhlites, to Martian interior components with and without additions of radiogenic decay products to Xe (Ott 1988; Ott and Begemann 1985; Ott et al. 2018; Mathew and Marti 2001, 2002; Swindle 2002). Figure 4.1 shows the most important endmembers—MI, Martian interior (Ott 1988); MA, Martian atmosphere as measured by *Viking*; and the fractionated signature, which can be extrapolated to EFMA—an elementally fractionated Martian atmospheric component. Also plotted are terrestrial air (AIR) and the two elementally fractionated terrestrial air signatures: noble gases dissolved in water (terrestrial water) and incorporated in terrestrial alteration minerals (EFA; Schwenzer and Ott 2006). There are several theories for the genesis of the elementally fractionated Martian atmospheric component, which have different implications for Martian climate and for rock–atmosphere interactions.

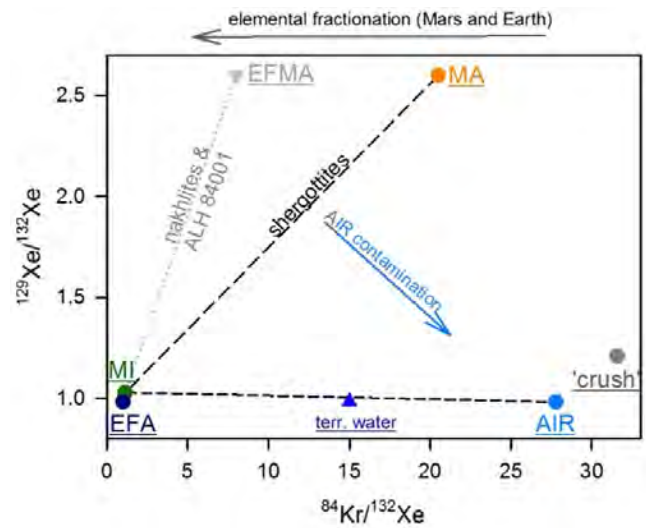

Fig. 4.1. Endmembers as commonly used in Martian meteorite heavy noble gas research. Endmembers are underlined, and mixing and fractionation trends are indicated by arrows and lines. "Crush" is an as yet unexplained component, first measured by Wiens et al. (1988).

4.2 Key Open Questions for Objective 4

Despite the wealth of information obtained through in situ measurements of Martian volatiles over the last two decades, there remain some unresolved conflicts between these different measurements—the most significant being the relative abundances of minor species nitrogen and argon in the atmosphere and a large difference (~10‰) between the carbon isotopic composition of atmospheric carbon dioxide measured by *Curiosity* and *Phoenix*. Similarly, the carbon isotopic composition of nakhlites is difficult to interpret with our current understanding of the CO_2 cycle. The noble gases in the meteorites show at least two—potentially three—different signatures: unfractionated heavy noble gas signatures in the shergottites, fractionated heavy noble gas signatures in the nakhlites, and the ancient meteorite ALH84001, but the latter two could also be two different signatures (Ott 1988; Murty and Mohapatra 1997; Swindle 2002; Schwenzer et al. 2018). It is thus clear that the absolute and relative abundances of various volatiles have changed through time via differentiation and magma ocean solidification, volcanic degassing, atmospheric loss, and interactions with the crust (McSween et al. 2010; Agee et al. 2013; Shaheen et al. 2014; Haberle et al. 2017; Filiberto and Schwenzer 2018). Understanding some of the key details, however, is hindered by constraints imposed by the different sources: in situ missions place the samples into a detailed geologic context, but are limited in their capability to heat samples (currently ~900 °C), which makes it impossible to quantitatively degas any sample. In contrast, Martian meteorites can be degassed fully in terrestrial laboratories, but they originate from unknown locations on Mars (although potential source craters have been suggested for a few) with no geologic context and an unknown history before their delivery as meteorites, and have experienced irradiation by galactic and cosmic radiation in space, which adds another layer of complexity in the interpretation of the environment and ejection of various minerals. Terrestrial weathering generates further complications. For example, the two most unique meteorites, ancient (~4 Ga) Martian orthopyroxenite ALH 84001 and Martian impact breccia, NWA 7034 and its pairs, are finds, rather than falls, as are most of the other known Martian meteorites (see Martian Meteorite Compendium [2017] for details). This makes a returned sample our only option to measure the full suite of volatiles within a Martian rock and connect it to its geologic context, especially for the more tightly bound magmatic and interior gases.

Martian basaltic magmas are presumably the ultimate mechanism of transfer of volatiles from the mantle to the surface and atmosphere (e.g., Hirschmann and Withers 2008; Johnson et al. 2008; Righter et al. 2009; Carr and Head 2010; King and McLennan 2010; Grott et al. 2011; Stanley et al. 2011; see Filiberto et al. [2016a] for a review). Volatile degassing from Martian magmas has been linked to both acidic weathering on the surface as well as regional and global climate change (e.g., Tosca et al. 2004; Poulet et al. 2005; Bibring et al. 2006; Carr and Head 2010; Ehlmann and Mustard 2012). Therefore, in order to understand the concentrations of volatiles in the crust, it is fundamental to first constrain the volatile budget of Martian magmas and the interior. Estimates for the volatile content of Martian volcanic rocks largely come from analyses of Martian meteorites, which are all relatively young and from a depleted source region. These studies have led to a significant debate about the past and present volatile content of the Martian interior (e.g., McSween et al. 2001; Médard and Grove 2006; Nekvasil et al. 2007; Filiberto and Treiman 2009; McCubbin et al. 2010, 2012, 2016b; Morschhauser et al. 2011; Gross et al. 2013; Taylor 2013; Jones 2015; Filiberto et al. 2016b). Estimates of the volatile content of ancient Martian magmas and the interior are seriously lacking because of a paucity of ancient volcanic samples in our collection.

The samples in our collection have sparked a debate about the evolution of the Martian atmosphere, which is currently still unresolved, 30 years after it was first discovered (Ott 1988): Kr/Xe ratios are fractionated against the modern Martian atmospheric ratios (as measured by *Viking*) in two groups of Martian meteorites: the nakhlites and ALH 84001. Both meteorite groups are older than the shergottites, which carry a modern atmospheric signature and which all have crystallization ages less than about 600 Ma. A key difference is that the shergottites carry no, or very little, alteration material, while nakhlites and ALH 84001 have undergone some hydrous alteration (e.g., Treiman 2005; Hicks et al. 2014; Shaheen et al. 2015a; Melwani Daswani et al. 2016). Moreover, they were ejected at different times from Mars than the shergottites, which could be important if the atmospheric composition changes on the time scale of millions of years (the time between ejection events) or shorter (Swindle et al. 2009). Thus, there are several ways to explain their elementally fractionated heavy noble gas fingerprint: (1) an internal (possibly crustal) gas reservoir, with its host rocks melted or assimilated into the meteorites' parent magmas (Gilmour et al. 1999); (2) elementally fractionated Martian atmosphere in the rocks' aqueous alteration minerals (Swindle et al. 2000); (3) fractional adsorption of atmospheric noble gases onto mineral surfaces (Gilmour et al. 2000); and (4) incorporation of an unfractionated Martian atmosphere, which was changed with time either seasonally or over millions of years (Swindle et al. 2009; see also Schwenzer et al. [2016] for a more complete literature list). Without establishing the daily, seasonal, and long-term variability of the Martian atmosphere, and the incorporation pathways into the rocks we already have, it is impossible to decipher the compositional clues from the data in hand. Sample return is the only way to obtain a sample with geologic context and Mars's contemporary atmosphere (Table 4.1).

Table 4.1. Key open questions for Objective 4: Understanding the origin and evolution of Martian volatiles.

KEY OPEN QUESTIONS: OBJECTIVE 4
Where did the volatiles on Mars originate?
How do the Martian crust and atmosphere interact and exchange material over time?
How has the Martian interior contributed to the volatile composition of the surface and atmosphere?
How has Mars's atmospheric composition evolved over geologic time?
How does Mars's atmosphere vary over seasonal, and other, time scales?

4.3 Why Returned Sample Studies Are Important for Objective 4

In addition to studying the current Martian atmosphere and ancient trapped gasses in Martian sedimentary, igneous, and impact samples, there is considerable knowledge to be gained by examining the unaltered compositions of sedimentary rocks, dust, and secondary minerals that are especially sensitive to climatic influences such as obliquity-driven changes. For example, detailed isotopic and chemical analyses of sediments from a variety of different ages on Mars would provide tremendous insight into the composition of the atmosphere and how it has changed through time, including details such as its oxidation state as well as the relative amounts of volcanic emissions and atmospheric loss. Results from the *Curiosity* rover indicate that it is possible to obtain high-resolution chemostratigraphic climate records from rhythmically bedded sedimentary rocks using in situ measurements (Grotzinger et al. 2015)—a capability that M-2020 is also expected to have (e.g., with SuperCam and PIXL). Analysis of selected returned samples from such in situ records would be extremely important in confirming and fully understanding such records. As another example, understanding the relationship between sedimentary rock, regolith, and secondary mineral compositions and the contemporaneous atmosphere would also greatly expand our understanding of kinetic and equilibrium isotope fractionation patterns, crucial for the interpretation of the paleoclimatic conditions on Mars by revealing how the sedimentary record responds to such changes. Finally, there is growing capability of applying a variety of radiometric techniques to dating of the time of sedimentation and obtaining such dates from climate-sensitive sedimentary sequences would greatly help to tie down the time scales of past climate changes.

With the advent of more precise and highly reproducible state-of-the-art techniques, it has become possible to measure the history of changes in volatiles, thus providing constraints on the causes of the massive environmental changes on Mars over the course of its geological history. In turn, these can be compared to similar understandings of Earth, and ultimately Venus, to develop genetic models for the causes and effects of environmental evolution on the terrestrial planets. Additionally, these measurements would help to constrain the early Earth climate models as well when we have a better understanding of how the atmosphere, hydrosphere, and geosphere interact in harsh environmental conditions, such as exposure to high-energy cosmic and galactic radiation (MeV- GeV), higher UV flux, and more intense solar wind.

4.4 Sample Investigation Strategies to Achieve Objective 4

The most sophisticated studies of volatiles that definitively allow separating reservoirs from rocks with complex histories (e.g., overprinting aqueous alteration) would be accomplished by analyzing returned solid samples with a variety of analytical techniques only possible in terrestrial laboratories and capable of analyzing detailed chemical and isotopic variations on a nanoscale and differential heating to correlate trapped volatile with the mineral compositions. In situ analyses on Mars (Fig. 4.2) demonstrate the promise of such techniques. Volatiles can be trapped in solids—as vesicles in volcanic rocks, implanted in shock melts, in igneous volatile-bearing minerals (such as apatite and amphibole), trapped during alteration mineral formation during hydrothermal events, and incorporated into some sedimentary minerals during diagenesis or by evaporation. In addition, many volatiles are incorporated in rocks during interactions with fluids of various sorts.

With the limitations of in situ atmospheric measurements to date, one, or preferably more, dedicated samples of the current atmosphere would also be required. The headspace gas in the sample tubes would be collected and analyzed as a supplement to understanding the nature of the solid samples and for evaluating any potential reactions that might have occurred inside the sample tube after collection. The likelihood of post-collection degassing, or other sample-gas interactions make the headspace gas less than ideal for evaluating small seasonal variations because it would be nearly impossible to eliminate the possibility of sample–gas interactions as a source of any variations observed. However, a dedicated set of atmospheric samples can provide a detailed baseline for seasonal variations that can be used to interpret results from headspace gas analyses.

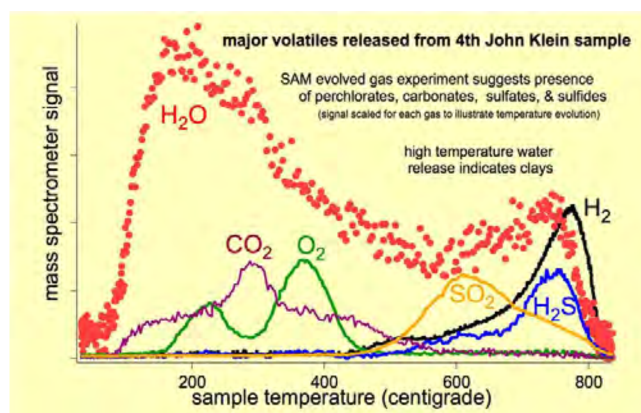

Fig. 4.2. The Sample Analysis at Mars (SAM) system on *Curiosity* has measured a variety of volatiles released from solid samples. The volatiles released from this mudstone were incorporated at some unknown time in the past. With returned samples, it would be possible to provide a more detailed accounting of what volatiles are associated with specific lithologies and potentially to obtain chronologic information about the time of incorporation. Figure from NASA-JPL-CalTech, based on data in Ming et al. (2014).

Table 4.2. Summary of sample-related investigation strategies to constrain and quantify the inventory, actions, and effects of Martian volatiles.

Investigation Strategies (IS) for Objective 4		
4	**Volatiles**	**Constrain the inventory of Martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.**
IS 4A	Determine the original source(s) of the planet's volatiles, and the initial isotopic compositions of the constituent gases in the atmosphere.	
IS 4B	Understand crustal–atmospheric interactions and feedbacks, especially for C, O, S, N, Cl, and H, in order to interpret present and past geochemical cycling on Mars.	
IS 4C	Quantify the history of the composition of the atmosphere, and the history of contributions from the interior (e.g., H, C, Cl, N, O, noble gases, and radiogenic products).	
IS 4D	Assess temporal (seasonal) variations in the composition of the present-day atmosphere to determine seasonal changes to both major and minor species as a means for evaluating crust–atmosphere cycling.	

We have defined four investigation strategies and 19 sets of measurements to constrain the inventory of Martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system (Table 4.2).

***Investigation Strategy 4A:* Determine the original source(s) of the planet's volatiles, and the initial isotopic compositions of the constituent gases in the atmosphere.**

The original source(s) is key information for understanding the formation of Mars, and by extension, all the terrestrial planets. Determining the original bulk and isotopic composition is complicated by the processes that occurred on the planet during its history. However, studies of the volatile content of minerals (i.e., apatite, amphibole, and nominally anhydrous minerals) in unaltered Noachian-aged samples can provide clues to the bulk volatile content of Mars. Further, there are some isotopes (such as the triple isotope system of O in rocks) that are expected to change little, and be highly diagnostic of their origin. Although the triple isotope system of O has been altered by mass-independent fractionation processes in the atmosphere, that of the Martian interior should have experienced only mass-dependent fractionation processes, and can be diagnostic of the source materials from Mars (Clayton 1993). Notably, the unusual basaltic breccia NWA 7034 has a $\Delta^{17}O$ value of 0.5‰, compared to the value of ~0.3‰ for all other Martian meteorites, suggestive of a surficial component (Agee et al. 2013). The higher $\Delta^{17}O$ value is likely due to ozone production with a mass-independent fractionation. Interestingly, this sample—despite being ancient and an impact breccia—shows shergottitic, modern atmosphere noble gas signatures (Cartwright et al. 2014), which questions the hypothesis derived from the other old Martian sample (ALH 84001; Murty and Mohapatra 1997) that fractionated atmospheric signatures indicate an earlier atmosphere. The carbon and oxygen triple isotopic compositions of carbonate minerals in ALH84001 indicate two generations of carbonates (~3.8 Ga formed by the interaction of magma with the atmosphere and carbonates formed at the time of ejection). Despite significant age differences, oxygen isotope anomaly remained constant ($\Delta^{17}O_{(CO3)}$ = 0.7‰) and suggests much less variations in the hydrological cycle of Mars (Shaheen et al. 2015b; Farquhar et al. 1998). The elemental abundances of the heavier noble gases (Ar, Kr, and Xe) may also contain diagnostic information about the origin of the volatile-rich material on Mars (Pepin and Porcelli 2002). The noble gas elemental ratios may be altered by atmospheric escape (Jakosky et al. 1994; Pepin 2000), or even seasonal or climatic variations (Swindle et al. 2009), but even in that case, measurement of the atmospheric ratios would provide insight into important properties of the Martian atmosphere.

Finally, the isotopic composition of xenon in the Martian atmosphere has long been known to be fractionated relative to what is presumed to be the primordial composition of the solar system (Swindle et al. 1986), presumably by some atmospheric loss process. However, the detailed primordial composition from which it is fractionated, and the mechanism and timing of that fractionation are still uncertain (Pepin 2000; Pepin and Porcelli 2002). The samples and measurements required for investigation of the evolution of the Xe isotopic composition, which can provide the data needed to determine the initial composition and hence source, are included within those discussed in Investigation Strategy 4C (Table 4.3).

***Investigation Strategy 4B:* Understand crustal–atmospheric interactions and feedbacks, especially for C, O, S, N, Cl, and H, in order to interpret present and past geochemical cycling on Mars.**

Although present conditions are much different from those earlier in Mars's history, quantifying the current interactions as well as the past interactions by analysis of volatile-bearing mineral phases would provide important constraints on the past history of volatiles as well as on current processes.

Modern-day interactions involve atmospheric chemistry without liquid water or where such water only exists in few molecule films. The surface of Mars is

Table 4.3. Samples and measurements implied by Investigation Strategy 4A.

Samples identified to advance Investigation Strategy 4A:

- Atmospheric gas sample, preferably at least two at two different points in the Mars year.
- Unaltered Noachian-aged igneous rock sample

Measurements identified to advance Investigation Strategy 4A:

- Measure the noble gas elemental abundance in the present Martian atmosphere.
- Measure the oxygen triple isotopic composition, C isotopes, and clumped isotopes in igneous rocks.
- Measure the sulfur quadruple isotopes of oxidized and/or reduced minerals in igneous rocks.
- Measure the indigenous noble gas signature of a geologically well-defined igneous sample.
- Measure the volatile content in unaltered apatite from a Noachian igneous sample.

covered with ~0.5–1% perchlorates as measured by *Viking*, *Phoenix*, and *Curiosity* (Leshin et al. 2013). Perchlorate is a strong oxidizing agent and may have implications for the preservation/destruction of organic matter on the surface of Mars (a potential source of energy for perchlorate reducing bacteria), and for the past and present hydrological cycle of Mars such as brine formation due to high deliquescence of chloride salts (Court et al. 2014; Kounaves et al. 2014a, 2014b). Analyzing the chlorine isotopes in different chlorine-bearing species would provide information on the kinetic and equilibrium processes occurring. The equilibrium δ^{37}Cl fractionation between perchlorate and chloride is approximately 73‰ at room temperature (Schauble et al. 2003). Terrestrial perchlorates have δ^{37}Cl values that are far less than the equilibrium fractionation (0 ± 10‰; Barnes and Sharp 2017), indicating strong isotopic disequilibrium during formation. The Cl isotope compositions of surficial Cl measured by the Mars Rover are scattered but generally less than −40‰ (Farley et al. 2016). This is in contrast to the measured δ^{37}Cl values of Martian meteorites, which range from −4‰ for mantle-derived samples to +8‰ for surface contaminated samples (see Barnes and Sharp [2017] for a review). The meteorite data are explained as two-component mixing between a mantle reservoir (δ^{37}Cl = ~−5‰) and a heavy crustal component due to loss of light ^{35}Cl to space. The discrepancy between the in situ data from the rover and meteorite samples remains unresolved, although it may be explained by lack of a robust calibration for the rover data. Additional samples would allow for the discrepancy to be resolved.

Regolith and dust samples are key components in the heterogeneous chemistry of the atmosphere. Analysis of SO_4 and CO_3 and respective O-isotope anomalies in these samples would be key to our understanding of how the atmospheric chemical reactions are preserved in different minerals. The SO_2 gas released during volcanic eruption is oxidized by various oxidizing agents in the atmosphere, which include ozone, hydrogen peroxide, water vapor, and hydroxyl radicals (Fig. 4.3). Similarly, the Δ^{17}O values of secondary mineral and rock samples would be an indirect measure of the oxidizing capacity of the Martian atmosphere. Sample analysis of rocks of different ages could be used to constrain the evolution of the Martian atmosphere. In addition, measuring the heavy noble gases would allow us to understand the incorporation of those gases into the regolith, thus providing important data points for the regolith as a (fractionating?) sink of nonreactive atmospheric species.

In contrast, water played a major role in mediating water–rock reactions in Mars's past, leaving behind an extensive and diverse record in outcrops at the Mars surface (e.g., Bibring et al. 2006; Murchie et al. 2009). Hydrous minerals have been observed in meteorites and in ancient stratigraphies exposed by rover missions. The key questions concern the nature of the environments,

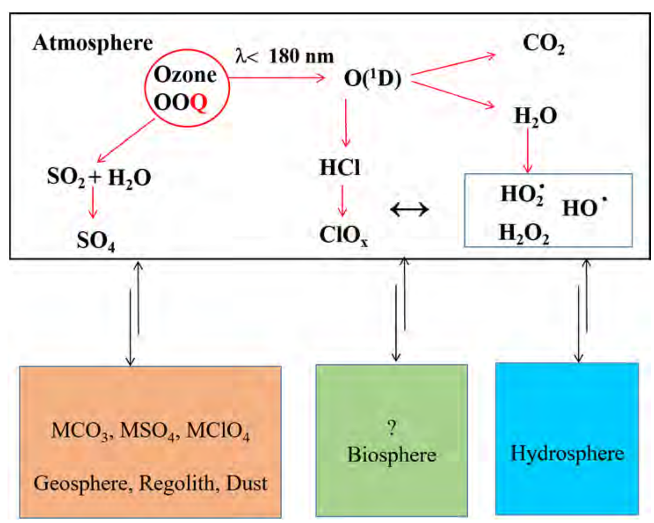

Fig. 4.3. Interaction of ozone with sulfur dioxide (SO_2) in the atmosphere to produce stable SO_4 molecule (Shaheen et al. 2013, 2014; Farquhar et al. 2001). Photolysis of ozone at wavelengths shorter than 184 nm produce excited oxygen atoms O(^{1}D), which can react with carbon dioxide to produce isotopic anomalous carbon dioxide, which is preserved as carbonate. Interaction of O(^{1}D) and water vapor can yield peroxy radicals and form hydrogen peroxides in the atmosphere. The oxygen triple isotopes of water adsorbed on mineral surfaces would reflect the odd oxygen cycle on Mars. Both O(^{1}D) and hydroxyl radicals can react with chlorine to produce perchlorates, thus preserving a signature of radical chemistry and photolysis of HCl in the atmosphere of Mars.

i.e., the temperature, pH, Eh, and geochemistry of waters from which these minerals formed; the timing of their formation; and the communication of waters with the atmosphere. For example, phyllosilicates are found globally in Noachian terrains across Mars. But it is debated whether they were formed by surface weathering, hydrothermalism/groundwater alteration, deuteric precipitation from lavas, or early in a primordial atmosphere (Ehlmann et al. 2011a; Carter et al. 2015; Meunier et al. 2012; Cannon et al. 2017). The answer has important consequences for the sources and sinks of Martian water, including whether these were primarily lost to space or to the crust, as well as for habitability. Petrology at sub-mm scale, D/H and oxygen isotope data, and—when possible—age dating hydrous mineral phases are necessary. Recent MSL data have confirmed at larger-scale findings from meteorites that aqueous alteration may have persisted longer in Mars history than previously believed with ages <2 Ga derived from jarosite (Martin et al. 2017). What climate processes control this long-term rock–water interaction is not understood.

A second example is the nature of the carbon cycle. Carbonates are found in select terrains seen in orbital data (Ehlmann et al. 2008; Michalski et al. 2013; Edwards and Ehlmann 2015; Wray et al. 2016), were observed in situ in rocks by the *Spirit* rover (Morris et al. 2010), but in Gale Crater were found in only in trace amounts in dust (Leshin et al. 2013) rather than in lake sediments, raising questions as to whether this is because of low pCO_2 (Bristow et al. 2017; Tosca et al. in press). Carbonates are also found in Martian meteorites, though their formation environment has been debated (Changela and Bridges 2010; Halevy and Head 2014). How the carbonates formed has important implications for past atmospheric pressure (Hu et al. 2015) and the percentage of atmosphere lost to space versus sequestered in rock. The way to differentiate various scenarios of atmospheric loss is to examine the isotopic C and O record preserved in carbonates. Such an isotopic record can only be understood, however, with petrology that informs the formation environment.

To that end, rock samples with mineral phases that trap volatiles from time periods on ancient Mars are of high priority for understanding Martian geochemical cycles, changing Martian climate and geology, and long-term crust–atmosphere interaction. The formation of organic compounds is also a crucial part of the carbon cycle, but is addressed in Sub-Objective 2.1 (Table 4.4).

***Investigation Strategy 4C:* Quantify the history of the composition of the atmosphere, and the history of contributions from the interior (e.g., H, C, Cl, N, O, noble gases, and radiogenic products).**

Table 4.4. Samples and measurements implied by Investigation Strategy 4B.

Samples identified to advance Investigation Strategy 4B:

- Dust and soil sediments.
- Atmospheric gas sample.
- Rocks with minerals recording volatiles including hydrous silicates, carbonates, sulfates, nitrates, and chlorides, particularly if the age of incorporation can potentially be determined.

Measurements identified to advance Investigation Strategy 4B:

- Measure the carbon and oxygen triple isotopic composition of CO_2 gas from atmosphere samples, and evolved from solid samples.
- Measure D/H, the oxygen triple isotope composition, and O-isotope anomaly ($\Delta^{17}O$) of water vapor in the atmosphere and phyllosilicate species and other hydrated mineral phases in ancient rocks.
- Measure the $\Delta\ ^{17}O$ values of hydrated and anhydrous silicates.
- Measure the $\Delta\ ^{17}O$ values of sulfate minerals in dust and rocks.
- Measure the C and O-triple isotopes of carbonates and water in rocks, dust, and regolith samples.
- Measure the chlorine and oxygen triple isotopic composition of perchlorate and chlorides on Mars.
- Analyze compound-specific isotopes of H, C, O, N, Cl, and S in molecular species in the atmosphere and in regolith, sediment, and rock samples.
- Measure sulfur quadruple isotopes and S-isotope anomalies ($\Delta^{33}S$, $\Delta^{36}S$) of sulfate in dust, regolith, rock, and soil samples.

Changes in the Martian atmosphere with time are clearly coupled to changes in the Martian environment. The contributions and losses to the atmosphere are key parts of those changes. Outgassing (most likely volcanic [Fig. 4.4], but perhaps related to impact) is the primary source for contributions to the atmosphere and degassing from Martian magmas has been linked to both acidic weathering on the surface as well as regional and global climate change (e.g., Tosca et al. 2004; Poulet et al. 2005; Bibring et al. 2006; Carr and Head 2010; Ehlmann and Mustard 2012). Analyses of the volatile content and S, Cl, C, and O isotopic ratios of minerals (i.e., apatite, amphibole, carbonate, and nominally anhydrous minerals) in unaltered Noachian-aged samples can provide clues to the primary contributions of volcanic degassing to the atmosphere. Further, it should also be possible to put constraints on the amount of outgassing by determining the history of the composition—elemental, molecular, and isotopic—of the Martian atmosphere.

The history of the composition of the atmosphere can also constrain loss processes, particularly when coupled with the measurements by the MAVEN mission

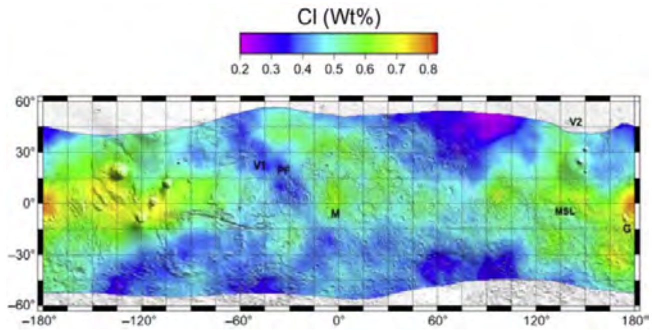

Fig. 4.4. Cl abundances are highest near volcanic vents, suggesting ongoing outgassing of Cl from the interior. Volatiles in key Noachian-aged minerals could provide key constraints on the amount and timing of such outgassing (figure from 2001 Mars Odyssey Gamma-Ray Spectrometer [U. Arizona/NASA]; original data from Keller et al. [2006] and Boynton et al. [2007], modified by Filiberto et al. [2018] [Table 4.5]).

of present-day loss. Returned samples are needed to determine the history of the Martian atmospheric composition by measuring samples that contain Noachian-aged unaltered igneous hydrous minerals, which contain samples of paleo-atmosphere that have exchanged with the atmosphere at known times in the past, and/or have minerals that formed from interactions with waters in contact with the atmosphere. The possibility of analyzing paleo-atmosphere is particularly intriguing for Xe. The terrestrial and Martian atmospheric Xe compositions have a similar degree of fractionation relative to likely primordial compositions. For Earth, Avice et al. (2018) have shown, by analysis of fluid inclusions in well-dated samples, that the fractionation in the atmosphere occurred much later than had previously been assumed. This suggests that if the Martian atmospheric Xe composition can be determined for samples which trapped atmosphere at well-determined points in time, it might be possible to use this to trace the history of atmospheric loss, as well as the original source of Martian Xe (and other volatiles). This would also enable comparison of the evolution of the climate of Earth and Mars.

Investigation Strategy 4D: ***Assess temporal (seasonal) variations in the composition of the present-day atmosphere to determine seasonal changes to both major and minor species as a means for evaluating crust–atmosphere cycling.***

Carbon dioxide, Ar, N_2, O_2, H_2O, H_2O_2, and D/H have been measured in situ to vary seasonally during the Martian year (Encrenaz et al. 2015; Franz et al. 2015; Villanueva et al. 2015; Trainer et al. 2016), and it has been proposed that other trace species might vary seasonally or following a partially modified pattern (e.g., Swindle et al. 2009). As seen in Fig. 4.5, measurements of methane have also been variable (Webster et al. 2015, 2018), with at least part of the variation correlated with time of the year (Webster et al. 2018). Seasonal variations may be driven by heterogeneity within polar cap reservoirs whose exchange of material drives seasonal atmospheric pressure variations. It is important to understand whether the observed variations are seasonal or the result of some other cause by addressing the possibility of seasonal variability. In addition, there are other features of Mars, from dust storms to Recurring Slope Lineae (which may be associated with the absorption and release of H_2O) that have a seasonal variability (McEwen et al. 2011; Bhardwaj et al. 2017), and it is

Table 4.5. Samples and measurements implied by Investigation Strategy 4C.

Samples identified to advance Investigation Strategy 4C:
- Rocks and regolith of known age containing hydrated minerals (carbonates, sulfates, sulfides, chlorides, perchlorates).
- Dry, clay-free dune material to study adsorption and dry implantation processes of atmospheric species in contrast to trapped fluid inclusions in next sample type.
- Any rock of known age containing minerals with trapped fluid inclusions.
- Highly shocked rock containing impact melt pockets or veins, where the timing of the shock event is known.
- Rock samples with the mineral phases above which preserve volatiles and may have formed from surface or near-surface waters—specifically ancient apatite-bearing samples and silicates with differing degrees of crustal assimilation.

Measurements identified to advance Investigation Strategy 4C:
- Analyze rocks/minerals/regolith that may have exchanged with the past atmosphere, at specific times in its history, e.g., carbonates ($\delta^{13}C$, $\delta^{17}O$, $\delta^{18}O$, $\Delta^{17}O$), sulfates ($\delta^{33}S$, $\delta^{34}S$, $\delta^{36}S$ and $\Delta^{33}S$, $\Delta^{36}S$), and perchlorates ($\delta^{37}Cl$, $\delta^{17}O$, $\delta^{18}O$, $\Delta^{17}O$) and adsorbed or chemically bound water, especially in hydrous minerals (δD, $\delta^{17}O$, $\delta^{18}O$, $\Delta^{17}O$).
- Analyze trapped gases within mineral inclusions and vesicles for the full range of atmospheric species, stable isotopes (especially H-, N-, and O-isotopes), and noble gas isotopic and elemental compositions.
- Analyze volatile species (e.g., H_2O, SO_3, H_2S, CO_2, Cl) preserved either as stoichiometric components of minerals (e.g., carbonates, sulfates, sulfides, chlorides, apatites, perchlorates) or adsorbed onto mineral/grain surfaces or trapped within fluid inclusions for their stable isotopic compositions (e.g., $^{2/1}H$, $^{18/17/16}O$, $^{13/12}C$, $^{15/14}N$, $^{36/34/33/32}S$, $^{37/35}Cl$), including clumped isotopes where possible.
- Analyze atmospheric gas implanted into impact melt.

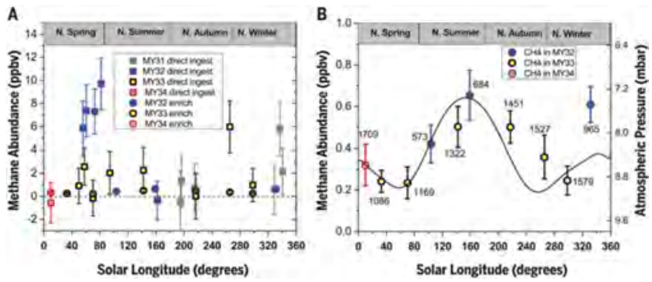

Fig. 4.5. Temporal variations in methane abundance of the Martian atmosphere at Gale Crater, as measured by the SAM Tunable Laser Spectrometer (TLS). Large excursions to several parts per billion by volume (ppbv) are seen in the full data set (A), as well as seasonal variations in the background levels measured with higher precision (Webster et al. 2018) (Table 4.6).

Table 4.6. Samples and measurements implied by Investigation Strategy 4D.

Samples identified to advance Investigation Strategy 4D:

- Atmospheric gas samples obtained at least two, preferably four, different seasons.

Measurements identified to advance Investigation Strategy 4D:

- Determine the seasonal variability of the elemental and molecular composition of the atmosphere, including, but not limited to, carbon dioxide, noble gases (particularly Kr and Xe), H_2O, oxychlorines, H_2O_2 and other oxidizing species, and methane.
- Analyze compound-specific isotopes of H, C, O, N, Cl, and S in molecular species.

important to know how the movement of volatiles influences, or is influenced by, these other effects. Finally, the amount and variability of oxidizing components at the surface (perchlorates, oxychlorines, atomic oxygen, superoxide and other ions, ozone, hydrogen peroxide (H_2O_2), and free radicals such as hydroxyl, perhydroxyl, etc.) and their heterogeneous catalytic destruction in the regolith is still unknown (see Kounaves et al. 2014a, 2014b; Carrier and Kounaves 2015; Lasne et al. 2016; Atreya et al. 2017), but some of these may be difficult to measure in a returned sample due to their transient nature or potential reactions during storage and transit. The gas in the headspace of samples collected in different seasons may provide some information on the temporal variability of various species in the atmosphere, but the volume of headspace is not likely to be large enough to make detailed measurements of trace species, and for reactive species, interaction between the gas and solid sample may make interpretation of the original composition difficult.

5 OBJECTIVE 5: RECONSTRUCT THE PROCESSES THAT HAVE AFFECTED THE ORIGIN AND MODIFICATION OF THE INTERIOR, INCLUDING THE CRUST, MANTLE, CORE, AND THE EVOLUTION OF THE MARTIAN DYNAMO

ORIGIN AND MODIFICATION OF THE MARTIAN CRUST, MANTLE, AND CORE

Why is this objective critical?	*Understanding the formation and modification of the Martian core, mantle, and crust is a key input to our planetary models.*
Which are the most important samples?	*A suite of diverse igneous rocks, oriented igneous or sedimentary rocks, ancient rocks, and impactites*

5.1 Introduction and Current State of Knowledge

Mars is a fully differentiated planet with a core, rocky mantle, and crust. Gravity measurements from orbiting spacecraft and ranging to surface landers provide some insights into the distribution of mass within the Martian interior. Recent modeling indicates a crust with an average density of ~2600 kg m^{-3} and an average thickness of ~42 km (e.g., Goossens et al. 2017). An important constraint on the thermochemical evolution of Mars is the complement of radioactive elements (U, Th, K) between the crust and mantle. Data from Martian meteorites and remotely sensed gamma-ray spectrometry are not internally consistent (meteorites are less enriched in these elements), suggesting an inhomogeneous distribution (e.g., Taylor et al. 2006). Mars has a fluid metallic core of radius 1300–1840 km (e.g., Folkner et al. 1997; Yoder et al. 2003; Khan et al. 2018). However, Mars lacks an active dynamo today and one of the fundamental questions about the evolution of Mars is the timing and consequences of the cessation of the dynamo.

In situ compositional and mineralogical measurements on the Martian surface, combined with analyses of Martian meteorites, indicate that most igneous rocks are lavas and volcaniclastic rocks of basaltic composition and cumulates of ultramafic composition (McSween 2015). Alkaline rocks appear to be more common in Early Hesperian terranes and tholeiitic rocks dominate younger Amazonian Martian meteorites (McSween 2015). The volcanic rocks provide indirect information on the composition of the mantle and core. Radiogenic isotopes in Martian meteorites indicate that distinct mantle source regions have remained isolated since earliest Martian history (e.g., Debaille et al. 2007). Feldspathic rocks represent the ultimate fractionation products—while they are present at Gale Crater (Morris et al. 2016; Cousin et al. 2017) (Fig. 1.19), they are rare from a remote sensing perspective (Christensen et al. 2005); granitoid rocks have not been identified.

The impact-driven delivery mechanism for the Martian meteorites (Head et al. 2002) biases in favor of more competent samples—young, coherent igneous rocks (e.g., Jones 1989; Warren 1994; Walton et al. 2008)—and against rocks that are more representative of the Martian crust (e.g., McSween et al. 2009). Comparisons of rock types found among the meteorites to those documented by landed missions demonstrates this bias unequivocally (McSween 2015); furthermore, of the over 100 Martian samples represented by the Martian meteorites, only one (NWA 7034 and its pairs) is a regolith breccia (e.g., Agee et al. 2013; Humayun et al. 2013).

Like other terrestrial planets, Mars has had a protracted history of impacts, including massive collisions that produced huge impact basins. Martian meteorites provide some insights into shock metamorphism and limited impact melting, although the effects of planetary-scale impacts are not recorded in these samples. Shergottites contain a variety of high-pressure polymorphs, as well as pockets of impact-melted glass. The role of impacts in producing subsurface geothermal systems has been advocated based on spectroscopic identification of altered minerals (e.g., Ehlmann et al. 2011a) and studies of terrestrial craters.

5.2 Key Open Questions for Objective 5

While the meteorites provide important insights into the nature of the silicate portion of Mars, including the origin of mantle components with differing geochemical characteristics (e.g., McCoy et al. 2011), they do not provide information on the composition of the original crust of Mars, nor the nature of the mantle sources from which ancient rocks at the Martian surface have been derived (e.g., igneous rocks at Gusev and Gale Crater). Indeed, whether the Martian mantle as viewed from the meteorites is applicable to all of Mars is also unknown (McCoy et al. 2011). The mostly young ages, prevalence of shock effects, and lack of information constraining the original orientations of meteorites has prevented determining the lifetime of the Martian dynamo and from measuring the direction of the ancient Martian magnetic field (Table 5.1).

Table 5.1. Key open questions for Objective 5: Understanding the origin and evolution of the Martian interior.

KEY OPEN QUESTIONS: OBJECTIVE 5
What was the long-term petrologic and geochemical evolution of Mars?
What was the intensity of the ancient Martian dynamo, did it undergo reversals, what phases record the paleomagnetism, and when did it cease to produce a magnetic field?
What is the history of core segregation/solidification and mantle convection, and did Mars ever experience plate tectonics?
Understand the nature, timing, and pervasiveness of shock metamorphism and melting on Mars.

5.3 Why Returned Sample Studies Are Important for Objective 5

The objective of reconstructing the history of Mars as a planet, including the fundamental processes of planetary differentiation into a primitive crust, mantle, and core, and the subsequent evolution of those components in composition and character, requires specific types of samples. In order to address the evolution of the mantle of Mars, samples that record igneous compositional diversity (in major, minor, and trace elements and isotopes) reflecting differences in mantle source characteristics and/or igneous fractionation processes are needed. Samples with U, Th, and K concentrations more typical of average Martian crust would enable better modeling of crust formation and heat distribution, and would complement anticipated heat flow data from the NASA InSight mission. Oriented samples with magnetic minerals are extremely valuable as records of the evolution of the Martian dynamo. In order to investigate the nature of the processes that formed and affected the primitive crust of Mars and that formed during the expected lifetime of the dynamo, samples as ancient and as unaltered as possible are required (Early Noachian and pre-Noachian). Impactites of varying type are needed to provide insights into the nature of cratering on Mars.

5.4 Sample Investigation Strategies to Achieve Objective 5

Strategies for collecting samples relevant to this objective are varied. In order to obtain a diverse suite of igneous rocks for Investigation Strategy 5A, a strategy similar to that outlined for Investigation 1.5 will be required; that is, sampling of igneous rocks encountered in “float” (cobbles or boulders along the rover traverse). A suite of samples appropriate for

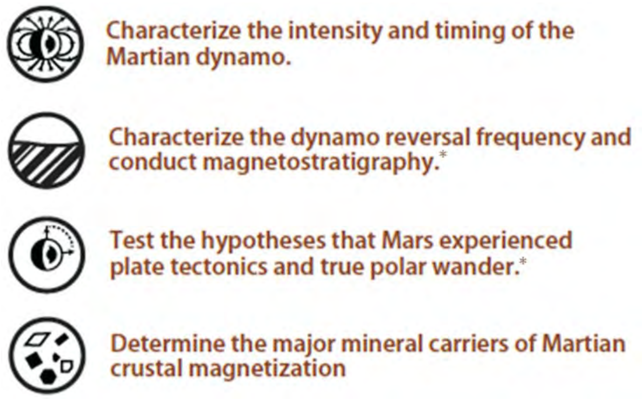

Fig. 5.1. Key science objectives related to paleomagnetic investigations. Those marked with an asterisk (*) require oriented samples After Weiss et al. (2018).

paleomagnetic studies (Investigation Strategy 5B)—specifically, oriented samples of fine-grained basaltic rock or clastic or chemical sedimentary rock—will require sampling from outcrops where the relative and absolute orientations of the samples are known. Key science objectives for paleomagnetic studies are given in Fig. 5.1. Samples needed to investigate the composition and nature of the early Martian crust (Investigation Strategy 5C) will require a strategy complementary to, and in parallel with, investigations of water/rock interaction during the pre-Noachian (Objectives 1.2, 1.3, 1.4). Last, the collection of samples that record the processes associated with impact cratering will require the detailed mapping of impactites at the landing site, and the careful selection of samples within their outcrop context; of the four sample types required for this Objective, this is perhaps the most challenging due to the complex nature of impactites.

We have defined four investigation strategies and 17 sets of measurements to reconstruct the processes that have affected the origin and modification of the interior, including the crust, mantle, core, and the evolution of the Martian dynamo (Table 5.2).

Investigation Strategy 5A: ***Constrain the long-term petrological evolution of Mars, from core segregation to crustal differentiation, and the origin of chemically distinct mantle reservoirs.***

Radiogenic isotopes record a time-integrated history of the planet's geodynamic evolution from its beginning to its present state, including core formation, crustal differentiation, and subsequent modifications by impacts and/or secondary alteration. By sampling igneous rocks, especially those of basaltic composition, geodynamical models can be developed to represent the entire global history of Mars. Such modeling is based upon results from the study of a diverse suite of igneous rocks (Sub-Objective 1.5) that can bring deep insights on magma

Table 5.2. Summary of sample-related investigation strategies to understand planetary-scale Martian geologic and geophysical processes, including those that have affected the origin and modification of the crust, mantle, and core.

Investigation Strategies (IS) for Objective 5		
5	**Geology**	**Reconstruct the processes that have affected the origin and modification of the interior, including the crust, mantle, core, and the evolution of the Martian dynamo.**
IS 5A	Constrain the long-term petrological evolution of Mars, from core segregation to crustal differentiation, and the origin of chemically distinct mantle reservoirs.	
IS 5B	Determine the thermal and magnetic history of the interior of Mars, including core crystallization, mantle convection, plate tectonics, true polar wander, and the nature of dynamo generation (intensity, secular variation, and reversal history).	
IS 5C	Determine the composition, petrology, and origin of the early Martian crust.	
IS 5D	Determine the chemistry, mineralogy, and geochronology (both relative and absolute) of shock-related rocks and mineral assemblages, impact-induced melts, impact-related hydrothermal alteration, and impact-deposited sediments.	

production and differentiation. Notably, the study of the abundance of highly siderophile elements (HSE) in a diverse suite of igneous rocks, coupled to short-lived chronometers (e.g., Hf-W), nucleosynthetic anomalies (e.g., Ru, Mo), and stable isotopic composition of siderophile elements (e.g., Pt, Ru) can provide insights on the timing and nature of metal-silicate segregation on Mars as a whole, and also on the meteoritic input that has gardened the Martian surface over the last 4.5 billion years. Additionally, by applying these approaches to all igneous rocks sampled, we can further constrain the bulk crust and mantle composition of Mars, as well as isotopically distinct reservoirs, and compare results to those obtained from the Martian meteorites. These studies will allow for the identification of any new geochemical reservoirs and determine whether they reside in the crust or mantle, and provide novel insights into Martian geodynamic evolution. The study of the elemental concentration and isotopic composition of moderately volatile elements (e.g., K, Zn, Rb) can be used to estimate the volatile inventory of Mars and the origin of the volatile delivery to Mars compared to the Earth and other planets, which are major unresolved questions.

While much has been inferred about the mantle of Mars from studies of Martian meteorites (e.g., Borg and Draper 2003; Herd 2003; McCoy et al. 2011; McCubbin

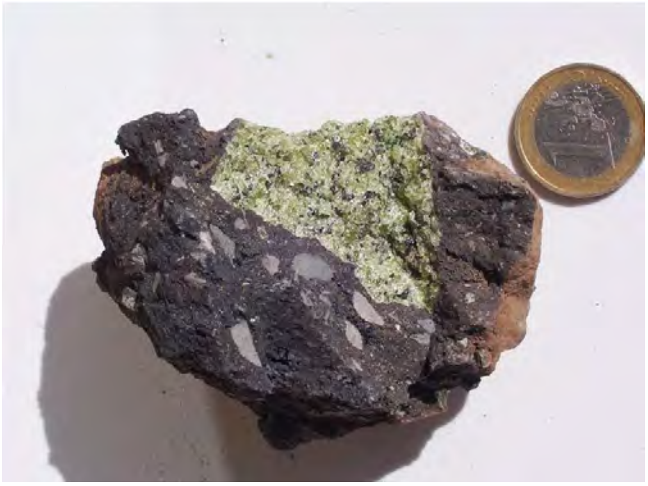

Fig. 5.2. An example of a peridotitic mantle xenolith from Earth (Creative Commons). Imagine if such a sample could be found on Mars!

et al. 2016b), no direct sample of the Martian mantle or lower crust exists among the meteorites. A sample of a mantle xenolith would provide potentially significantly improved constraints on the mineralogy of the Martian interior and allow tests of mineralogy inferred from meteorite studies (e.g., Bertka and Fei 1997) as well as information complementary to that obtained by geophysical methods (e.g., Khan and Connolly 2008) including expected results from the NASA InSight Mission (https://mars.nasa.gov/insight/). A sample suite that included mantle xenolith(s) with basaltic melt counterpart(s) would enable the full characterization of Martian mantle sources and their derived melts (e.g., Fig. 5.2). A xenolith from the lower crust would also be very useful, for placing constraints on the composition of the primitive crust of Mars and for assessing models involving assimilation of/contamination with ancient crust (e.g., Herd et al. 2002) (Table 5.3).

Table 5.3. Samples and measurements implied by Investigation Strategy 5A.

Samples identified to advance Investigation Strategy 5A:

- A suite of igneous rocks and breccias representative of the diversity of available igneous rock types. Basalts and highly fractionated rocks are especially informative. An ultramafic igneous rock within a basaltic igneous host rock would represent a potential mantle or lower crustal xenolith.

Measurements identified to advance Investigation Strategy 5A:

- Measure variability in the mineralogy, texture, mineral proportions, and mineral chemistry (major, minor, and trace element), and bulk compositions (major, minor, and trace element, and radiogenic isotopes) of all igneous rocks and igneous clasts within brecciated samples, or as xenoliths in basaltic samples in order to classify them relative to other igneous rocks from Mars, and determine whether they represent primary mantle melts or melts affected by interaction with other mantle or crustal sources or components.
- Measure radiometric ages (e.g., U-Pb, Ar-Ar, Sm-Nd, Lu-Hf, Rb-Sr) of each igneous rock from as many systems as feasible in order to obtain crystallization ages and ages of source regions. (Note that although the Hf-W system would be of interest, this may or may not be possible using samples collected by M-2020, because of potential contamination from the drill bit.)
- Measure stable isotopic compositions (e.g., K, Zn, Rb, O, H) of minerals and bulk rock samples in order to quantify primary igneous and secondary (e.g., alteration or other modification) processes.
- Measure the HSE abundances of all breccia clasts and each igneous rock type sampled in order to gain insights into the original composition of Mars and core–mantle segregation and mantle differentiation processes

Investigation Strategy 5B: ***Determine the thermal and magnetic history of the interior of Mars, including core crystallization, mantle convection, plate tectonics, true polar wander, and the nature of dynamo generation (intensity, secular variation, and reversal history).***

Although Mars does not have an active dynamo today, spacecraft measurements of the Martian crust (Acuña et al. 2008) and paleomagnetic measurements of Martian meteorite ALH 84001 indicate that a core dynamo was active on Mars by at least the Early Noachian epoch (Weiss et al. 2004, 2008; Cassata et al. 2010). One of the key hypothesized mechanisms for and the subsequent transition to the current cold dry conditions is that the loss of this early dynamo led to stripping of the atmosphere by the solar wind. Paleomagnetic measurements of ancient returned samples could test this hypothesis by establishing the relative timing of the decline of the dynamo to climate change as recorded by surface rocks, especially if the orientations of the returned samples were known (Fig. 5.3). Furthermore, because the original orientations of Martian meteorites are unknown, all Mars paleomagnetic studies to date have only been able to measure the paleointensity of the Martian field. Therefore, paleomagnetic studies from returned Martian bedrock samples would provide unprecedented geologic context and the first paleodirectional information on Martian fields. By measuring the paleomagnetic inclination of rocks as a function of time, such data could be used to test the hypotheses that early Mars underwent plate tectonics and/or true polar wander. The latter could potentially be distinguished from the former even with data from

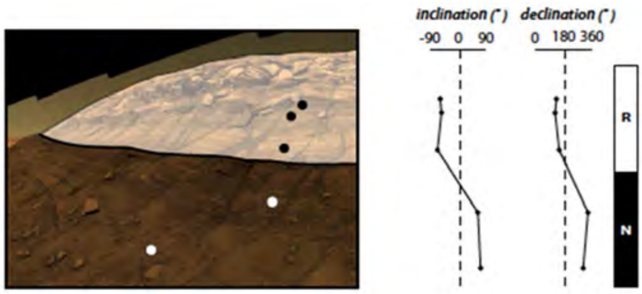

Fig. 5.3. Schematic diagram showing the utility of oriented samples obtained in situ for paleomagnetic investigations. Image at left from NASA/JPL/Cornell.

a single landing site if the observed rates of polar wander are higher than can be achieved by plate motion (e.g., Evans 2003). Furthermore, these data could be used to characterize the dynamo reversal frequency with magnetostratigraphy, which could be used for relative chronometry and to constrain the mechanism of the Martian dynamo and core flows. Furthermore, determining how magnetization direction and intensity varies over the Mars 2020 landing site would constrain the coherence scale of crustal magnetization, thereby providing a window into the how tectonics and the time-variability of the dynamo has jumbled up the magnetization in the region. In addition, the times that the dynamo initiated and ceased may constrain the thermal evolution of the Martian core and mantle. Finally, paleomagnetic studies of folds and conglomerates, including e.g., Early pre-Noachian megabreccia blocks, would constrain the peak temperature and timing of aqueous alteration on samples returned from these materials, which would be important indicators of the preservation state of their biosignatures (Weiss et al. 2018; Mittelholz et al. 2018). In particular, the demonstration that the clasts of a conglomerate are randomly magnetized and/or the demonstration that the magnetization of samples around a fold hinge is better clustered after bedding-corrections could demonstrate that the rocks had not been heated above ~200 °C and that their ferromagnetic minerals (oxides and sulfides) are primary rather than the products of oxidation and sulfidization.

We note that this Investigation Strategy has deep links with Investigation Strategy 3C but nevertheless is fundamentally distinct. Investigation Strategy 3C focuses on determining the *timing* of the dynamo history and polar wander by coupling paleomagnetic measurements on well-dated rocks. By comparison, Investigation Strategy 5B focuses on determining the mechanism and geometry of the dynamo, establishing the existence of plate tectonics and true polar wander, constraining the nature of Martian ferromagnetic minerals, and constraining the thermal and aqueous alteration history of the samples. None of the latter topics require well-dated samples and several of them do not relate to planetary history at all (magnetic mineralogy, and alteration history of the samples). As a result the two Investigation Strategies have differing optimal sample suites: Strategy 3C requires well-dated rocks, ideally oriented, while Strategy 5B requires samples with a more diverse set of properties but with less focus on their absolute age (Table 5.4).

***Investigation Strategy 5C:* Determine the composition, petrology, and origin of the early Martian crust**

The processes involved in the formation of the earliest Martian crust are largely unknown, but likely involved aqueous alteration under neutral to acidic conditions during the Noachian to early Hesperian (Sub-Objectives 1.2, 1.3, 1.4). Initial formation may have involved magma ocean crystallization, analogous to what happened on the Moon, followed by overturn or large-scale stratification (e.g., Ehlmann et al. [2016] and references therein). The main purpose of this investigation is to "see through" aqueous alteration of the early Martian crust, in order to determine its composition and the processes (e.g., magma ocean crystallization) involved in its formation. Samples of igneous rock as relatively unaltered clasts within a suite of probable Noachian-aged altered rocks, or relict mineral clasts within sedimentary deposits such as alluvial fans, would be required to address this investigation (Table 5.5).

Table 5.4. Samples and measurements implied by Investigation Strategy 5B.

Samples identified to advance Investigation Strategy 5B:

- Igneous rock sample (ideally fine-grained basaltic rock) or sedimentary (clastic or chemical) samples for which the orientation during the time they became magnetized is known (Fig. 5.3).

Measurements identified to advance Investigation Strategy 5B:

- Measure the absolute direction and intensity of magnetization in oriented Martian bedrock materials as a function of time.
- Determine the major mineral carriers of Martian crustal magnetization by measuring their rock magnetic properties.
- Measure the ages of rocks that contain geomagnetic anomalies to constrain the age of the dynamo and Martian magnetic history.

Table 5.5. Samples and measurements implied by Investigation Strategy 5C.

Samples identified to advance Investigation Strategy 5C:

- A suite of ancient rocks that are the most likely candidates for the original crust of Mars, including those subjected to the least amount of apparent aqueous alteration.

Measurements identified to advance Investigation Strategy 5C:

- Measure variability in the mineralogy, texture, mineral proportions, and mineral chemistry (major, minor, and trace element) of rocks that have been modified by water/rock interactions.
- Identify crosscutting relations, and measure radiometric ages of primary (igneous) and secondary (alteration) minerals with permissible mineralogy.
- Measure stable isotopic compositions (C, H, O, N, S) of minerals from veins and cavities.
- Determine the composition of fluid inclusions and reconstruct trapping temperatures from phase relationships within those inclusions.
- Determine the conditions of (metamorphic) equilibration of rocks, including temperature and pressure.

Investigation Strategy 5D: ***Determine the chemistry, mineralogy, and geochronology (both relative and absolute) of shock-related rocks and mineral assemblages, impact-induced melts, impact-related hydrothermal alteration, and impact-deposited sediments.***

The impact cratering record of Mars includes a wide range of crater sizes, ages, crater densities, and conditions of impact and preservation (e.g., Ehlmann et al. [2016] and references therein). In addition to the timing of specific impact events (in particular of large, basin-forming events such as Isidis), much remains unknown regarding the relationship between impact cratering and induced hydrothermal activity, and the duration of hydrothermal systems as a function of crater size (Osinski et al. 2013). Improvements to our understanding of cratering as a process for modifying the Martian surface are needed. Although impact processes are recorded in Martian meteorites, none of them are impact breccias (sensu stricto); however, an impact breccia from a major basin-forming impact event would provide insights into the nature of the target rocks (Fig. 5.4), whether clays were formed during widespread alteration conditions at the Martian surface, or via impact-induced alteration (e.g., Tornabene et al. 2013), and potentially the compositions of subsurface ice, paleofluids and/or atmospheric gases from the time of impact (e.g., Usui et al. 2015). Sedimentary deposition in the form of fallback breccia or ejecta flow may be important in the impact process on Mars; a sample of rock that records this process would be useful, as long as it can be distinguished from rocks deposited by water or wind (e.g., Objective 1.1).

Fig. 5.4. Melt-bearing breccia (aka suevite) from the Mistastin Lake impact structure, Canada; courtesy G. Osinski (Table 5.6).

Table 5.6. Samples and measurements implied by Investigation Strategy 5D.

Samples identified to advance Investigation Strategy 5D:

- Hydrothermally altered impact breccia or in-place rocks modified by impact-induced hydrothermal activity; any impactite or heavily shocked rock of any type (Fig. 5.4).

Measurements identified to advance Investigation Strategy 5D:

- Measure variability in the mineralogy, texture, mineral proportions, and mineral chemistry (major, minor, and trace elements) of rocks that have been formed or modified by impact-induced hydrothermal activity.
- Determine crosscutting relations, and measure the radiometric ages of the primary and secondary minerals with permissible mineralogy.
- Measure the isotopic composition (e.g., Cr) of rocks that have been formed by impact in order to determine the origin of the meteoritic material impacting Mars.
- Determine crosscutting relations, and measure the radiometric ages (e.g., by Ar-Ar, Rb-Sr, etc.) of the primary and secondary minerals with permissible mineralogy.
- Constrain the shock pressures and temperatures experienced by the minerals and melts during impact.

6 OBJECTIVE 6: UNDERSTAND AND QUANTIFY THE POTENTIAL MARTIAN ENVIRONMENTAL HAZARDS TO FUTURE HUMAN EXPLORATION AND THE TERRESTRIAL BIOSPHERE

UNDERSTAND ENVIRONMENTAL HAZARDS TO HUMAN EXPLORATION	
Why is this objective critical?	*The gaps in our knowledge related to Martian environmental hazards, risk to the terrestrial biosphere, and the safety of engineered systems need to be closed.*
Which are the most important samples?	*Airfall dust, and surface regolith containing dust-sized particles; representative fractions of other samples.*

6.1 Introduction and Current State of Knowledge

Mars has long been a captivating target for future human exploration, but there remain many unknowns in terms of potential hazards posed by the Martian environment. In fact, sending humans to Mars is incompatible with current Planetary Protection Policy requirements, which were developed for and based on robotic missions. These policies will need considerable revision to accommodate the dramatically different planetary protection paradigm for human missions. To inform human planetary protection policy development, new data with a high degree of confidence will be required, necessitating the evaluation of diverse Martian samples for their nature and potential hazards, including samples representative of the globally circulating dust.

In planning human missions, there are three principal classes of hazards to be considered: (1) those that could cause harm (biological or chemical) to human explorers visiting (or living on) the Martian surface, (2) hazards to the systems (mechanical or electrical) that human explorers would rely on to survive on Mars, and (3) potential biological hazards that could be transported back to Earth. All three concerns are included in the current COSPAR Policy for Human Missions to Mars, which provides general principles and implementation guidelines, but not quantitative requirements for future human missions (COSPAR Planetary Protection Policy 2011). A robotic Mars sample return mission would present an ideal opportunity to improve our understanding of these hazards (Bass et al. 2012) and to address key knowledge gaps of importance to planetary protection concerns (Spry et al. 2018).

Fig. 6.1. Apollo 17 astronaut Eugene Cernan covered in lunar dust (Photo Credit: NASA). Pervasiveness of lunar dust on exterior of suits and interior of lunar module demonstrates exposure hazards for astronauts and the back-contamination of Earth.

As demonstrated during the Apollo program, once the crews opened the seals to their landed systems for EVA explorations, it was impossible to avoid getting dust onto the outsides of the spacesuits as well as into the living quarters (Fig. 6.1) (Gaier 2005). The lunar dust caused more than just acute health hazards (Armstrong and Collins 1969; Sheenan 1975; Cain 2010), it also caused numerous space suit problems, from jammed joints and degraded seals, to abrading multiple layers of the Kevlar-like material on the boots (Cooper et al. 2008). Such effects may be amplified on Mars for several reasons. For example, the longer duration of the currently envisaged Martian exploration missions have anticipated surface exposures of weeks-to-years, compared with the lunar landed missions on the order of hours-to-days (e.g., NASA 2009). In addition, the presence of local and global dust storms, as well as the effects of spacecraft ascent/descent engine plumes, will lift and transport dust long distances (Fig. 6.2).

Fig. 6.2. Mastcam views of the change in the Spirit rover dust coverage. (Photo Credit: NASA). Pervasiveness of Martian dust illustrates exposure hazards for astronauts and potential back-contamination of Earth.

Furthermore, on the Martian surface, there is an extra concern about biological hazards to human explorers and engineering systems (in addition to the geochemical hazards; e.g., Winterhalter et al. 2018).

Given these challenges, there is a high likelihood that crews will be exposed to uncontained Martian material. In addition, the action of returning astronauts to Earth at the end of the mission could raise the possibility that the terrestrial biosphere may be exposed to Martian material. While the general scientific consensus is that this would pose a low, but as yet undefined risk to both human health and the terrestrial biosphere (NRC 2002), it is essential to fully understand all possible outcomes. The NASA Draft Test Protocol for detecting possible biohazards in Martian samples returned to Earth (Rummel et al. 2002) outlines a preliminary description of the measurements required to determine the presence of extant life and assess if dust is a mechanism for its transport. This test protocol is now over 15 years old, and was developed in the context of a previous Mars sample return concept that is not representative of current sampling plans or the anticipated returned sample suite. The protocol will need to be updated in the coming months and years to reflect advances in instrumentation, refinement in knowledge of the sample material to be returned, and an increased understanding of Mars and of life itself.

Attention must be paid to the method and statistics of assessing the biohazard risk of a returned sample set that might have material from multiple environments (NRC 2009), particularly in light of our improved knowledge of Mars and recognition of at least 12 different habitable environment types (Ehlmann and Edwards 2014). Such updated approaches need to be integrated with preliminary scientific examination, as they are complementary and intrinsically related (Haltigin and Smith 2014; Kminek et al. 2014). In addition, the revisions should take into consideration terrestrial technological advances in the intervening period, particularly in the context of robotic handling (e.g., surgical equipment and microelectronics industries) and updated life detection instrumentation and technologies (e.g., -omics type approaches) (Johnson et al. 2017; Reuter et al. 2015; Dauphin et al. 2009).

6.2 Key Open Questions for Objective 6

The gaps in our knowledge that would be informed by returned samples fit into three primary groups: those that are associated with human health hazards, terrestrial biosphere risks, and safety of engineered systems (Fig. 6.3). Accordingly, the key open questions identified for Objective 6 are listed in Table 6.1.

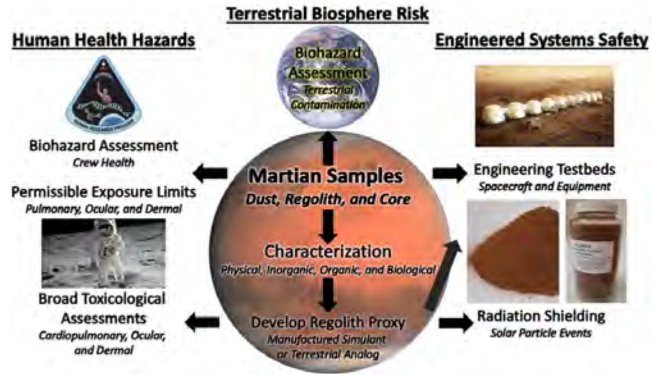

Fig. 6.3. Schematic of Objective 6—Constrain the nature of the potential hazards to future human exploration. The five primary knowledge gaps are highlighted.

Table 6.1. Key open questions for Objective 6: Understanding potential hazards to human exploration.

KEY OPEN QUESTIONS: OBJECTIVE 6
Does the Martian environment contain biological hazards that might have adverse effects on Earth and terrestrial beings (Planetary Protection)?
Does the Martian environment contain biological hazards that might have adverse effects on a future mission?
Does the Martian environment contain geochemical hazards that might have adverse effects on a future crewed mission?
What are the physicochemical differences (bulk, fine, and trace) between the global dust and near-surface/surface regolith material?
Is the Martian surface safe for human operations (e.g., hardware maneuverability, structural integrity, and launch- and landing-pad safety)?
Can Martian regolith be effectively utilized as a radiation shield for humans on the surface?

6.3 Why Returned Sample Studies Are Important for Objective 6

While sample return from Mars has been repeatedly recognized as being important for answering many basic science questions about Mars (NRC 2011), its relevance to future human missions has also been acknowledged as critical (NASA 2012) and international workshops have focused on important Planetary Protection knowledge gaps that must be addressed (Race et al. 2015; Kminek et al. 2018; Spry et al. 2018) before human missions are possible. Many of the knowledge gaps identified in key areas may be addressed by future MSR returned sample materials. Importantly, to address questions in Objective 6, returned samples are needed for toxicological and engineering assessments and also for use in generating simulants for larger-scale hazard evaluations and research.

For Objective 6, some measurements are proposed that would require samples that cannot be collected directly by M-2020. The M-2020 sampling system does not have a dust filtration system, so it cannot acquire concentrated airfall dust directly from the atmosphere. It does have the "waterfall" drill bit (see Appendix 3) which would be able to collect granular material from the light-toned drift deposits on the Martian surface, which are thought to represent geological accumulations of airfall dust. It is not yet known whether one of the elements of a potential sample-retrieval mission would have an additional sampling system that would be able to collect dust samples in either larger quantity or directly from the atmosphere. In addition, the iMOST team is not fully at consensus on the distinction between "required" and "desired" for some of the measurements in this section. Clearly, further discussion, including with a broad set of stakeholders for human missions to the Martian surface, is warranted. This would make a difference in determining whether a second MSR mission, with different sampling equipment, is on the critical path ahead of the first human landing.

Under the international consensus COSPAR policy for planetary protection, material returned from Mars is to be treated as Category V, Restricted Earth Return (COSPAR 2011) and presumed hazardous (and kept under strict containment) until proven otherwise (Kminek et al. 2017). The concern is that the uncontrolled release of Martian materials could contain an unknown Martian organism (should one be present) that might present a threat to Earth, as a potential human pathogen and/or a replicating entity, with the potential to disrupt the terrestrial ecosystem more broadly, if released.

In the context of biohazard assessment, interrogation of the returned Mars samples has the potential to assess the level of threat from Martian material, informing and reducing risk for subsequent missions, including crewed ones. The same measurements to test the scientific hypothesis that there is Martian life in the sample can also be employed to evaluate the competing hypothesis of planetary protection concern: that there is no detectable life in the sample (Allwood et al. 2013; Kminek et al. 2014). Additionally, under the COSPAR policy, a program of life detection and biohazard testing and/or a proven sterilization process is an absolute precondition for the controlled distribution of any portion of the sample and would be required in order to perform some of the other analyses proposed in this document.

Some of the key planetary protection knowledge gaps were assessed in a series of international workshops that flowed from NASA's NPI-NPR plans (2012). In 2015, NASA workshop with nearly 100 participants identified key knowledge gaps in three important areas: microbial and human health, technology and operations for contamination control, and natural dispersal of microbes on the Martian surface (Race et al. 2015). Subsequently, a COSPAR workshop "Refining Planetary Protection Requirements for Human Missions" (held in 2016; Kminek et al. 2018) prioritized the gaps and identified potential ways and locations where research and technology development (R&TD) could be done to address them. A follow-on COSPAR workshop (May 2018; report to be hosted at https://planetaryprotection.nasa.gov/humanworkshop2018), the 2nd Workshop on Refining Planetary Protection Requirements for Human Missions, identified potential locations and mission opportunities in four time periods that offer ways for addressing R&TD gaps (NASA Planetary Protection Office; Kminek et al. 2018). Many of the identified knowledge gaps can be addressed fully or in part by interrogation of samples returned from Mars under the current MSR campaign paradigm.

Looking ahead, "breaking the chain of contact" when leaving Mars is a requirement for containment (to a high level of assurance) of all returning Mars material. Additionally, it also prevents the uncontained return to Earth of any mission items that have been exposed to the Martian environment. Although this step is technically achievable for robotic missions, it is *not* for a crewed mission. Guaranteeing prevention of human contact with the Martian dust in all credible circumstances is judged to be impossible with currently available or foreseeable crewed exploration technologies (NRC 2002; NASA 2009; COSPAR 2011). *Thus, it is necessary to determine in advance whether or not Martian material is biologically hazardous.*

There would only be a limited quantity of Martian material returned to Earth on sample return missions, yet there are many questions related to crew health and engineering applications that will require research related to exposure to Martian dust and regolith. Characterization of returned Martian samples would enable synthesis of high-fidelity simulants. Not only will these simulants be utilized to complete broad toxicological assessments (necessary to fill gaps in knowledge resulting from limited quantities of primary samples) but these simulants can also be utilized in an array of engineering testbeds (e.g., landing/take-off platforms, rover mechanics, etc.) as well as understanding potential ways in which Martian regolith can be utilized as a protective agent (i.e., radiation shield). Knowledge of each of these elements is necessary before crewed missions are sent to Mars. Mars sample return is essential in order to acquire this knowledge.

6.4 Sample Investigation Strategies to Achieve Objective 6

Analyses under this MSR investigation activity (alongside other relevant in situ Martian, lunar, or terrestrial studies) will aid in addressing how to reduce future planetary protection risk levels to acceptable, but as yet undefined, standards. Overall, the particular areas needing attention pertain to understanding and quantifying the potential Martian environmental hazards to future human exploration and the terrestrial biosphere. We have defined four investigation strategies (IS) (Table 6.2) and 20+ sets of measurements (Tables 6.4, 6.5, 6.6, and 6.7) aimed at addressing and understanding potential hazards to human exploration. The combined IS areas include research that focus on biological, geochemical, and engineering aspects of mission design and implementation.

The first two investigation strategies relate to understanding any direct **hazard to human health** from Martian dust, as outlined in the MEPAG report of 2015: *successful Mars exploration, including future human missions to the Mars surface, requires a functional crew free from debilitating health risks imposed by the Martian environment, and with the capability to return to Earth safely*.

Investigation Strategy 6A: ***Biohazard assessment. Determine if Martian environments contain biological hazards that might have adverse effects on a future mission (e.g., crew health or spacecraft systems) or on humans or other terrestrial species if uncontained Martian material were released on Earth.***

The risks in question in Strategy 6A relate to (1) the inevitable exposure of surface crew to Martian dust containing potential biohazards and (2) the potential exposure of humans and other terrestrial species on Earth to uncontained Martian biohazards, within returned materials. In a crewed mission, such materials would certainly be on the outside of the vehicle and habitats, as well as within the cabin or even within the astronauts' bodies when the crew leaves Mars. The first step is to assess if the returned samples contain a biohazard. It is important that this is performed first since it is possible that (1) if the samples contain microorganisms they may not be virulent which could unnecessarily limit further investigation of the returned samples or (2) virulent microorganisms might not be identifiable and overlooked. Given the importance of this investigation, it is vital to assess an array of samples that originate near, or are representative of, the area in which the human Martian surface operations would take place. Although properties of the surface dust are the main concern for the human explorers, information on the subsurface is also important since the crew would disrupt the surface and be exposed to the subsurface during daily operations (e.g., structure building, sample collection). Some of this uncontrolled material would likely make the journey back to Earth.

Table 6.2. Summary of sample-related investigation strategies to understand potential hazards to human exploration.

Investigation Strategies (IS) for Objective 6		
6	**Understand and quantify the potential Martian environmental hazards to future human exploration and the terrestrial biosphere.**	**Nature of Hazards Addressed**
IS 6A	Determine if Martian environments contain biological hazards that might have adverse effects on a future mission (e.g., crew health or spacecraft systems) or on humans or other terrestrial species if uncontained Martian material were released on Earth.	Biohazard assessment
IS 6B	Assess risks to crew health. Set appropriate permissible exposure limits. Characterize the regolith/dust and generate high-fidelity simulants to perform geochemical analyses and broad toxicological assessments.	Geochemical and physical health hazards
IS 6C	Assess broader risks to crew performance. Characterize the regolith/dust samples and generate high-fidelity simulants to perform an array of spacecraft and equipment safety evaluations.	Geochemical and physical engineering hazards
IS 6D	Evaluate the Martian regolith for its efficacy as a radiation shield for humans on the surface from a solar particle event. This would include determination of the types and quantity of radiation that can be shielded and the degree to which other biologically relevant particles are formed after passing through the substrate.	Radiation hazard mitigation

The first step of Strategy 6A is to determine if extant life is present in the Martian material and, if possible, characterize it. Understanding the biochemical nature of presumed Martian life is important in order to determine if the biohazards are Martian or from terrestrial contamination and also if airborne dust is a mechanism for its transport. Such tests would help establish whether sending crew to the Mars surface would inevitably result in exposure to a Martian organism, while simultaneously confirming or refuting established wisdom on the limits of life. Previous studies (Rummel et al. 2002) have suggested that approximately 10% of the total MSR materials may be required for adequate biohazard assessment. However, other studies have proposed that the required quantity could potentially be reduced if biohazard assessment *and* science studies are performed concurrently on the same sample (Allwood et al. 2013). Because of the limited amount of the returned sample, strategies would be employed to allow for thorough assessment while minimizing sample usage. Furthermore, it is recognized that other authorities may recommend a different sampling approach in a future update of the biohazard assessment protocol.

Exposures, analyses, and characterizations should then establish what threat a Martian organism (or community of organisms) could pose to the mission (e.g., pathogenicity to the crew, the ability to compete for or spoil critical resources, and the threat of degrading hardware/systems performance) and to the terrestrial ecosystem upon return (e.g., humans, animals, plants, resources, etc.), resulting from the inevitable exposure of the crew on the Martian surface and potential release of uncontained Mars material that will result from the return of any crew to Earth (even with strict crew quarantine as with Apollo). These tests also address whether sending crew to the Martian surface would inevitably result in exposure to a Martian organism, while simultaneously confirming or refuting established wisdom on the limits of life.

Presumably, the degree of dust mixing observed on Mars (for Martian dust) means that a sample of fine (airfall) dust will likely be a representation of the geological, chemical, and (potentially) biological character of the whole planet. Therefore, if Martian organisms exist on the surface of Mars, airborne dust would be a mechanism for their transport. Notwithstanding breakdown processes that might occur to biological molecules as a result of exposure to the Martian surface environment, it is considered that analytical techniques with the necessary sensitivity could be applied to such a sample to bound the occurrence and abundance of biological systems on a planet-wide basis. Limitations of the airfall sample include dilution of biological signal and the uncertainty in context and age of the dust with respect to any biological activity. Evaluation of the biohazard threat of regolith samples from nearby the location to be visited would give greater certainty about biohazard threat in proximity to the human landing site. However, because there is currently no selected landing site for a human mission, achievement of this desirable aim is unlikely to come through the Mars 2020 mission.

In establishing if there is, or ever was, life on Mars, it is considered that the best preserved evidence would probably be in a location protected from radiation incident at the surface, potentially at least 2 m below the surface. It would need to be established that the sample obtained has a high probability of being sufficiently old to have been protected beyond the timeframe of an obliquity cycle, when redistribution of water at the global scale would have most likely caused biomarkers of Martian origin to have been deposited in the regolith material or to have migrated into the sample material. Dust remaining on the surface of the sample tubes or hardware of a Mars Sample Return campaign (e.g., Mars 2020 rover) may represent the most pristine samples available as well as the most likely material to be exposed to humans. If possible, the dust can be removed upon return from the hardware/tube exterior and accumulated for testing or the unadulterated hardware/sample tubes themselves can be used for the toxicology assessment (e.g., placed within an occupied animal cage).

Table 6.3 describes the ideal samples types for a comprehensive biohazard assessment of the Martian surface and Table 6.4 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigations of Strategy 6A. Together, this combined approach will help us move toward determination of whether Martian environments contain biological hazards that might have adverse effects on future missions or on humans or other terrestrial species if uncontained Martian material were released on Earth.

Investigation Strategy 6B: ***Assess risks to crew health. Set appropriate permissible exposure limits. Characterize the regolith/dust and generate high-fidelity simulants to perform geochemical analyses and broad toxicological assessments.***

Extensive knowledge gained from an understanding of lunar dust toxicity (LADTAG 2013) is potentially applicable to Martian dust. Despite these data, uncertainties exist in setting a Martian dust permissible exposure limit, uncertainties that could be directly addressed through return of Martian dust samples. Ideally, sufficient volumes of primary Martian sample material would be utilized in well-designed animal

Table 6.3. Descriptions of ideal sample types for a comprehensive biohazard assessment of the Martian surface.

Sample Type	Justification
Concentrated airfall dust	The degree of mixing observed for Martian dust means that a sample of fine (airfall) dust will likely be a representation of the geological, chemical, and (potentially) biological character of the whole planet. Therefore, if Martian organisms exist on the surface of Mars, airborne dust would be a mechanism for their transport. Notwithstanding breakdown processes that might occur to biological molecules as a result of exposure to the Martian surface environment, it is considered that analytical techniques with the necessary sensitivity could be applied to such a sample to bound the occurrence and abundance of biological systems on a planet-wide basis.
Surface regolith	A limitation of the airfall sample is dilution of biological signal; others include the uncertainty in context and age with respect to any biological activity. Evaluation of the biohazard threat of regolith samples from the location to be visited would give greater certainty about biohazard threat in proximity to the human landing site. The proximity requirement of the sample to the human exploration zone is tbd.
Subsurface regolith	In establishing if there is, or ever was, life on Mars it is considered that the best preserved evidence would likely be in a location protected from radiation incident at the surface, potentially at least 2 m below the surface. It would need to be established that the regolith sample being obtained has a high probability of being old enough (i.e., has been buried at the 2 m depth) to have been protected beyond the timeframe of an obliquity cycle, when redistribution of water at the global scale would have most likely caused biomarkers of Martian origin to have been deposited in the regolith material.
Rock cores	As with the subsurface regolith, in establishing if there is, or ever was, life on Mars it is considered that the best preserved evidence would likely be in a location protected from radiation incident at the surface, potentially at least 2 m below the surface. It would need to be established that the regolith sample being obtained has a high probability of being old enough (i.e., has been buried at the 2 m depth) to have been protected beyond the timeframe of an obliquity cycle, when redistribution of water at the global scale would have most likely caused biomarkers of Martian origin to have migrated into the sample material.
Dust on sample tubes or hardware	The dust remaining on the surface of the sample tubes or hardware may represent the most pristine samples available as well as the most likely material to be exposed to humans. If possible, the dust can be removed from the hardware/tube exterior and accumulated or the unadulterated hardware/sample tubes can be used for the toxicology assessment (e.g., placed within an occupied animal cage).

Table 6.4. Samples and measurements implied by Investigation Strategy 6A.

Samples identified to advance Investigation Strategy 6A:
- Concentrated airfall dust.
- Subsurface regolith, as deep as possible from the same location as the samples for IS 6B.
- Rock cores, as deep as possible from the same location as the samples for IS 6B.
- Dust on surface-exposed sample tubes or hardware.

Measurements identified to advance Investigation Strategy 6A:
- Perform the agreed biohazard assessment protocol, presumably comprising nondestructive characterization (e.g., by CT screening) followed by destructive testing.
- Ecotoxicity tests (TBD selected exposure tests on representative species).
- Identification of the molecular/genetic material within the returned sample(s) (performed in collaboration with Sub-Objective 2.3).

testing to generate inhalation permissible exposure limits (PEL) and to assess dermal and ocular exposures. However, if insufficient quantities of Martian regolith samples are available, these limits may need to be based on testing with high-fidelity simulants or other analogs (while characterizing and accounting for the inherent uncertainties in these approaches when setting the PEL). The uncertainties associated with assessing dermal and ocular risks through these types of surrogate tests are likely to be less than when assessing inhalation exposures, and may also utilize larger size fractions of the primary dust or high-fidelity simulants, if sufficient quantities are available.

Proper understanding of the inherent toxicological properties of Martian dust is crucial to the setting of appropriate crew exposure limits used to address human health and performance risks (because of exposure through inhalation, dermal contact, ocular contact, and ingestion of dust or contaminated food or water [Cain 2010; Scheuring et al. 2008; Scully and Meyers 2015; Lam et al. 2013]). The physical and chemical properties, as well as the abundance of trace chemicals (e.g., metals and other inorganics such as perchlorates) contained within the Martian dust have been characterized by Mars rover missions, and risks can partially be assessed from these profiles (dependent on assumed exposure route and site-specific factors). However, questions still remain that can only be answered by testing with Martian regolith samples, such as the extent to which oxidative properties or other inherent factors would affect toxicity. Taking a

Table 6.5. Samples and measurements implied by Investigation Strategy 6B.

Samples identified to advance Investigation Strategy 6B:
- Concentrated airfall dust, either from a drift deposit or collected from the atmosphere.
- Near-surface/surface regolith containing dust-sized particles.

Measurements identified to advance Investigation Strategy 6B:
Physicochemical characterization
- Bulk elemental composition (e.g., by EMPA) and mineralogy determination (e.g., by XRD) to help understand the origin of any toxicity.
- Particle size analysis. Determine particle size distribution within the samples as well as confirm size fraction for exposure studies.
- Total surface area and pore space (e.g., by BET). Understand the amount of total surface area available for geochemical reactivity and direct interaction with biological systems.
- Morphology (e.g., by SEM). Analyze the shapes of Martian dust grains with a grain size distribution sufficient to assess their potential impact on human soft tissue (especially eyes and lungs)
- Chemical reactivity (e.g., by ion chromatography and spectroscopy). Characterize soluble ion concentrations, chemical reactions that can occur, and oxidative potential upon humidification.

Toxicological Assessment (in order of priority)*
- Assess Martian dust pulmonary toxicity (adverse impacts to the respiratory system) relative to the known toxicity of lunar dust and well-characterized reference dusts (e.g., titanium dioxide and quartz).
- Assess Martian dust cardiovascular toxicity (adverse impacts to the cardiovascular system) relative to the known toxicity of lunar dust and well-characterized reference dusts (e.g., titanium dioxide and quartz).
- Assess Martian dust ocular hazard (adverse impact to the eye) using representative unfiltered Martian drift surface dust. Particle size is not a practical limitation.
- Assess Martian dust dermal hazard (irritation/abrasion of skin) using representative unfiltered Martian drift surface dust. Particle size is not a practical limitation.

*Ideally, permissible exposure limits (PELs) should be determined utilizing primary Martian material, whereas broad toxicological assessments can utilize high-fidelity simulants.

similar path to that taken with the assessment of lunar dust (LADTAG 2013; Lam et al. 2013), toxicological testing of returned Martian dust would probably consist of several investigations. Although analysis of a bulk sample is important, different size fractions will be investigated in order to understand the composition and physicochemical properties of the particles most relevant to exposure site (e.g., pulmonary, cardiovascular, ocular, and dermal). Special focus will be given to respirable size fractions (≤10 μm and ≤2.5 μm in diameter) and the differentiation of local versus global dust.

Table 6.5 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 6B and move toward assessment of risks to crew health and performance. The studies listed in Table 6.6 will be performed utilizing the samples characterized as part of IS 6A.

The **following two strategies** are relate to the **safety of engineered systems**. As outlined in the MEPAG report of 2015: *it is necessary to understand the ways in which the Martian environment affects engineered systems. Successful human missions to the Mars surface requires a functional crew free from debilitating health risks imposed by the Martian environment, and with the capability to return to Earth safely.*

***Investigation Strategy 6C:* Assess broader risks to crew performance. Characterizing the regolith/dust samples and generate high-fidelity simulants to perform an array of spacecraft and equipment safety evaluations.**

To ensure crew safety and mission success, spacecraft and equipment designed for future human exploration missions to Mars will undergo rigorous ground testing and evaluation with Mars regolith and with dust simulants on Earth. Crewed systems will be certified to meet new or unique requirements that were not imposed on earlier robotic science missions. For example, spacesuit developers will have to demonstrate suit fabric resistance to Martian regolith/dust abrasion damage and ability to remove dust before bringing suits into habitable areas for maintenance. What is more, the scale of human systems—with landers more than 20 times the size of the *Curiosity* rover—may require very large quantities of Mars regolith/dust simulant to support ground testing and certification. Several types of simulants, of varying degrees of fidelity, will be used to evaluate the interaction of the Mars environment with crewed systems. Regolith properties will be important to some evaluations, such as mobile system trafficability; however, dust properties will be much more important because dust will coat virtually all external surfaces, and is more likely to be transported into crew cabins.

Table 6.6 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 6C and move toward assessment of risks to crew health and performance. The studies listed in Table 6.6 will be performed utilizing the samples characterized as part of IS 6A.

***Investigation Strategy 6D:* Characterize the Martian dust/regolith for its efficacy as a radiation shield for humans on the surface from a solar particle event. This would include determination of the types and quantity of radiation that can be shielded and the degree to which**

Table 6.6. Samples and measurements implied by Investigation Strategy 6C.

Samples identified to advance Investigation Strategy 6C:
- Representative unfiltered Martian airfall dust.
- Near-surface regolith containing dust-sized particles.
- Subsurface regolith.
- Core sample.

Measurements identified to advance Investigation Strategy 6C:
- Analyze the particle grain shape, surface area, and size distribution to understand how dust will be "kicked up" by large descent engine plumes or large rovers, as well as to validate fluid system component performance, such as filters.
- Abrasivity testing will help evaluation of pressure seal degradation, hatch leakage, optical surface degradation (windows, visors, instruments), damage to protective coatings and rotating equipment (such as bearings or pumps), and wear on spacesuits and flexible insulation materials.
- Determination of electrical and magnetic properties to assess potential problems, such as charged dust particles resulting in static shock equipment damage, as well as to evaluate potential useful properties, such as electrostatic dust cleaning techniques.
- Determination of thermal and optical properties to evaluate dust-coated radiators, solar arrays, electrical cables, and light fixtures.
- Chemical characterization for crop growth experiments (including perchlorate uptake assessment), hardware corrosion assessments, membrane function, and chemical process hardware interactions (such as ISRU or water extraction)
- Surface area analysis to determine how much the sample can adsorb; may also be important for developing simulants used in plant growth studies.
- Physical and mechanical properties characterization to assess the interaction of structural elements with the Mars environment.

other biologically relevant particles are formed after passing through the substrate.

Mars's atmosphere and regolith provide some protection from galactic cosmic rays (GCR) and solar irradiation. Studies have shown that additional shielding of common materials such as aluminum or polyethylene does not significantly reduce the GCR exposure (Slaba et al. 2013). A comparison of the attenuation characteristics for different subgroups of Martian rocks and the Martian regolith indicates that changes in composition have negligible effect on overall shielding properties because of the similarity of their constituents (within 0.5 and 1%; Kim et al. 1998). In addition, it is shown that on the Martian surface, almost any amount of aluminum shielding increases exposure levels for humans. The increased exposure levels are attributed to neutron production in the shield and Martian regolith as well as the electromagnetic cascade induced in the Martian atmosphere. This result is significant for optimization of vehicle and shield designs intended for the surface of Mars.

Table 6.7. Samples and measurements implied by Investigation Strategy 6D.

Samples identified to advance Investigation Strategy 6D:
- Representative unfiltered Martian airfall dust.
- Surface regolith.
- Subsurface regolith.

Measurements identified to advance Investigation Strategy 6D:
- Determine the extent of protection that different thickness layers of regolith provide from different types and dosages of radiation.
- Determine the extent of damage produced by irradiation of the surface, and assess the potential for biologically significant species to be produced.

Table 6.7 summarizes the type of samples that should be collected, and the associated measurements required in order to carry out Investigation Strategy 6D and move toward assessment of the efficacy of the Martian regolith as a radiation shield for humans on the surface. The studies listed in Table 6.7 will be performed utilizing the samples characterized as part of IS 6A.

7 OBJECTIVE 7: EVALUATE THE TYPE AND DISTRIBUTION OF IN SITU RESOURCES TO SUPPORT POTENTIAL FUTURE MARS EXPLORATION

UNDERSTAND POTENTIAL IN SITU RESOURCES	
Why is this objective critical?	*Identifying potential Mars resources, and understanding how they could be utilized, is enabling for future exploration*
Which are the most important samples?	*Regolith of several different kinds, rock with hydrated minerals, airborne dust*

7.1 Introduction and Current State of Knowledge

Considerable recent planning has focused on the potential importance of Mars's in situ resources to support future human missions (e.g., Drake 2009; Portree 2011; ICE-WG 2015; MEPAG 2015b; Abbud-Madrid et al. 2016). From the perspective of saving mass on the outbound journey, the single most

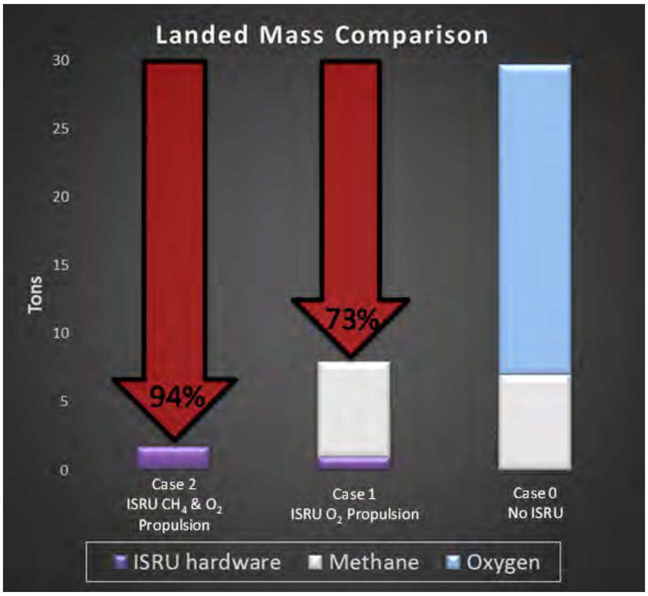

Fig. 7.1. Results from an ISRU baseline study (Kleinhenz and Paz 2017) conducted for the Evolvable Mars Campaign showing the benefits of ISRU propellant production. Case 0: the propellant mass needed for a Mars ascent vehicle (Polsgrove 2015). Case 1: oxygen is produced from the Mars atmosphere and methane is transported from Earth. Case 2: methane and oxygen produced on Mars from the atmosphere and soil water.

Fig. 7.2. Conceptual example of exploration systems using ISRU capabilities.

significant need is for propellant for a Mars Ascent Vehicle (Polsgrove 2015; see Fig. 7.1). A methane–oxygen propellant system was baselined in the Mars Design Reference Architecture (Drake 2009), partly because of its potential in situ availability. By mass, 78% of that propellant is oxidizer, which is most readily obtained by conversion of the CO_2 that dominates the Martian atmosphere into oxygen and CO, which could be used to manufacture methane. Although the Martian atmosphere is a crucial resource, for this purpose, measuring its composition more precisely than is already known, by means of analysis of returned samples, is considered not necessary. Some of the notional ISRU concepts that may be involved in future human missions are shown in Fig. 7.2.

In situ production of the methane fuel requires a source of hydrogen, which can be combined with the carbon from the Martian atmosphere. Water is known to be present in significant quantities on Mars and could serve this need. But the interest in water as an in situ resource goes well beyond the manufacture of propellant. Water can provide many of the needs of a research station, such as life support, radiation shielding, and agriculture.

In situ resource utilization is not limited to propellant and life support production. Local material could also be used as feed stock for construction, including for structures, roads, and additive manufacturing. Native salts (Mg, Ca, and Na perchlorates and Ca-Chloride) in the Martian regolith could be used as water absorbents for closed loop life support systems or for capture of the limited atmospheric water. Mars regolith could also be used to supplement agriculture (Wheeler 2004). Hydroponic plant growth requires around 90 kg of fertilizer to provide dietary calories for one person per year (365 days) (Lunn et al. 2017). Nutrients from regolith, nitrates in particular, could be used to reduce terrestrial fertilizers as would recycled waste materials. These in situ nutrients could be extracted and incorporated into a fertilizer, or the regolith itself could be enriched into a soil which would provide more buffering to the plant roots.

Water: A planet-wide survey of water resources down to a depth of about 1 m was provided by the Gamma Ray Spectrometer Suite on the Mars Odyssey spacecraft, suggesting that even at the equator, the near-surface regolith contains 3–7% water-equivalent hydrogen (Boynton et al. 2002). However, the GRS pixel size is approximately 400 km, which is not amenable to planning specific engineering implementations. Neutron data collected by the Dynamic Albedo of Neutrons (DAN) instrument along the pathway driven by MSL measure total hydrogen (modeled as "water-equivalent hydrogen" or WEH) over a 3 m wide, 60 cm deep footprint. Most of these data are best modeled by a two-layer structure, where the upper layer is ~20 cm thick, and has less hydrogen (average 1.5–1.7% WEH) than the lower layer (average 2.2–3.3% WEH) (Litvak et al. 2014; Mitrofanov et al. 2014). The total amount of H_2O released from samples analyzed by MSL to date has been around 2 wt% for each sample (values range ~1.1 ± 0.5 up to ~2.5 ± 1.6 wt% (Vaniman et al. 2014). The CheMin data from MSL's first three samples show the presence of the hydrated minerals bassanite, akaganeite, and smectite along with an unidentified amorphous component, although with an uncertainty in the concentration of ~50% (Vaniman et al. 2014). Perchlorate was first identified as a significant component of Martian regolith (0.4–0.6 wt%) by the *Phoenix* mission (Cull et al. 2010), it was probably seen by *Viking* (Navarro-Gonzalez et al. 2010), and the SAM data indicate the presence of oxychlorine minerals with abundances as high as 1.05 ± 0.44 wt% Cl_2O_4 equivalent (Sutter et al. 2017). Some of the water content of the Martian regolith may be in the form of perchlorate hydrates. In the Rocknest sample, CheMin did not detect any hydrous crystalline phases, and yet SAM showed water release upon heating (Leshin et al. 2013). Most of that water must therefore be in an X-ray amorphous component. The specifics of the mineralogy make a big difference in understanding the quantity of water that could be expected to be released with temperature in an ISRU recovery operation.

Ice: The presence of water in the form of ice deposits is also of great interest to ISRU. Recent studies have identified substantial ice sheets at depths of ~1 m at a latitude of ~55°N (Dundas et al. 2018). Permafrost also exists at shallower depths and in great quantity, at latitudes higher than ~60° (both N and S) (Mellon et al. 2009). There are some important trade-offs between accessing and utilizing the subsurface ice versus accessing surface hydrated material; these trade-offs are still under engineering evaluation.

Atmosphere: The use of the Mars atmosphere in the production of oxygen is a critical part of ISRU propellant and life support production strategy. While understanding the Mars atmosphere is important, the technologies to perform this processing are well underway. A lot of valuable data will be collected by the MOXIE investigation on the M-2020 mission (Hecht et al. 2017; McClean et al. 2017).

Other resources: Beyond water, a Mars research station would have needs for local fabrication and production of many materials that could have a local source. One example is concrete for fabrication of building materials, possibly robotically (Lee et al. 2015). Additive manufacturing using local regolith, has also been explored (Jakus et al. 2017) and the idea of refining materials to extract other resource has also been discussed (e.g., regarding lunar regolith; Landis 2007). These and other uses of in situ resources would benefit greatly from laboratory analysis of the composition and morphology of Martian rock and regolith.

7.2 Key Open Questions for Objective 7

This objective specifically addresses exploration, where identifying and utilizing Mars resources is an enabling capability, particularly for human exploration. Orbital data and landed surveys have identified useful resources such as water. Yet knowledge is lacking regarding how the resource is bound (e.g., hydration state for water), the physical and thermophysical properties of the materials, and what other useful mineralogical components may exist (Table 7.1).

7.3 Why Returned Sample Studies Are Important to Objective 7

Any of these in situ utilization processes require definition of the resources to influence equipment design and resource budgeting. Prospecting via orbital and landed surveys as well as technical demonstrations are necessary. Sample return would play a role in supporting this planning, including ground truthing of orbital surveys. Sample return can provide a more comprehensive picture of the available resources and their properties. When considering long-term human presence this information becomes more critical to site selection, architecture decisions, and hardware design. Likewise, detailed assays of a returned sample may

Table 7.1. Key open questions for Objective 7: Understanding potential in situ Mars resources.

KEY OPEN QUESTIONS: OBJECTIVE 7
What is the concentration, mineralogic basis, and variation of water in Martian surface materials?
What are the physical and thermophysical properties of Martian surface materials of relevance to the design of potential future ISRU surface systems?
What is the potential of Martian granular material for use for in situ agriculture?
Contingent on discovering significant concentrations of metals of potential future interest, can we predict the possibility of significant deposits on Mars?

identify other resources, hazards and contaminants, and/or utilization potentials not yet considered. It should be noted that the impact and requirements of sample return for ISRU is contingent on mission planning. A sample return prior to ISRU flight demonstrations may be critical to ISRU. Sample return after ISRU technology demonstration missions would help clarify data and improve subsequent hardware. The regional dependencies of resources and material properties in the Mars 2020 exploration region may not fully represent an ISRU target site, but would provide valuable information on "typical" Mars regolith.

Water resources: The form and concentration of water within the regolith is critical to exploration architecture planning and engineering design. While orbital and landed surveys offer enough information for initial designs and technology demonstrations, long-term human missions would benefit greatly from more comprehensive information. Sample return would permit chemical and geotechnical characterization of the surface material. This allows for refinement of engineering designs and architecture decisions and enables development of high-fidelity simulants for terrestrial tests. Lunar ISRU technology development has benefited from the analysis of samples returned from the Moon. While viable ISRU water resources may exist as either hydrated minerals or as water ice, the focus on this sample return is the former (Fig. 7.3). While water ice samples would equally beneficial, the current Mars 2020 landing sites are within 19°N of the equator, where ice is not present. Therefore, the sample objectives listed here do not encompass ice samples.

Atmospheric resources: Characterizing the Mars atmosphere is not explicitly included in these objectives. Instruments that will be available on Mars 2020 will adequately cover this without the need for samples. However, characterization of the dust would be of value to enable better predictions of lifetime, performance, and risk factors for candidate mechanical systems.

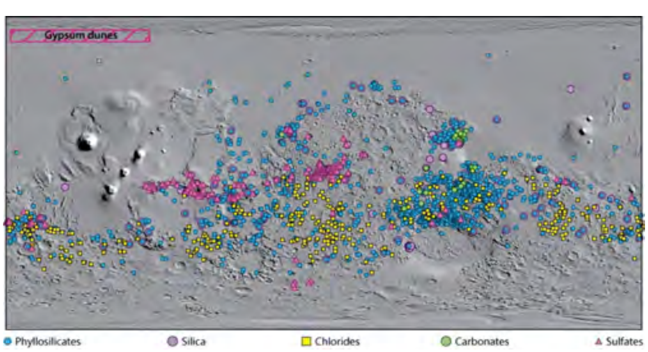

Fig. 7.3. A map of aqueous mineral deposits from orbital data (Ehlmann and Edwards 2014) as potential sources of water for ISRU purposes.

Other resources: Beyond water, local resources may have application to construction, additive manufacturing, and agricultural uses. Understanding the feasibility and value of these applications would benefit from laboratory analysis of the composition and morphology of Martian rock and regolith.

7.4 Sample Investigation Strategies to Achieve Objective 7

In support of this objective, we recognize four significant returned sample investigation strategies, which are listed in Table 7.2. One is to measure the concentration and mineralogical state of water in certain carefully selected samples. A second is to understand the physical attributes of Martian surface materials, so that engineered systems could be designed to interact with them properly (note that this overlaps significantly with one of the investigation strategies within Objective 6). The third is to assess quantitatively the potential of Martian granular material for use in possible future on-Mars agriculture. There are important subtleties related to the presence or absence of specific beneficial or deleterious components to agriculture, especially those that are water soluble. The fourth strategy, related to potential Martian ore deposits, is completely contingent on encountering and collecting samples with high concentrations of potentially useful commodities. It is important to note that carrying out these strategies would not be enough

Table 7.2. Summary of sample-related investigation strategies to constrain the potential usefulness of Martian in situ resources for future human explorers.

Investigation Strategies (IS) for Objective 7		
7	**ISRU**	**Evaluate the type and distribution of in situ resources to support potential future Mars exploration.**
IS 7A	Determine the concentration, mineralogic basis, and variation of water in Martian surface materials and identify associated chemical constituents that may negatively impact potential end-use processes of this water.	
IS 7B	Characterize the physical and thermophysical properties of Martian surface materials to influence the design of potential future ISRU surface systems and to develop high-fidelity simulant material for use in ISRU engineering test beds.	
IS 7C	Identify components in Martian granular material that may be beneficial or detrimental to its use for in situ agriculture.	
IS 7D	Contingent on discovering significant concentrations of natural metallic resources, characterize the source materials to enable predictions of where and how such deposits may be concentrated on Mars.	

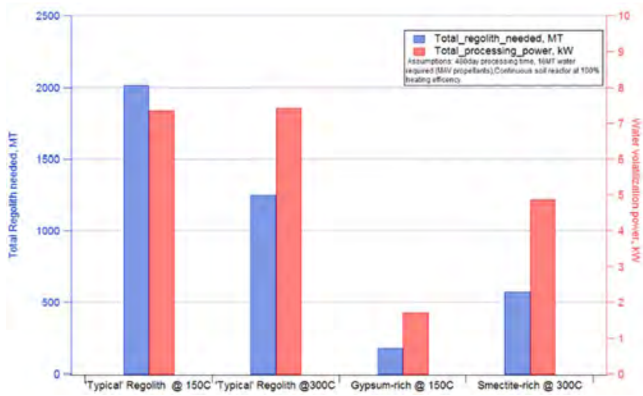

Fig. 7.4. An engineering trade showing the processing temperature and quantity of regolith needed to extract water from potential Mars aqueous minerals as defined in the MWIP study (Abbud-Madrid et al. 2016).

to complete the objective of evaluating the potential for successful Martian ISRU operations. Substantial in situ exploration is also required. For example, sample analysis by itself can give highly precise and accurate estimates of concentration/quality, but it cannot be used to estimate quantity. Thus, we view these strategies as necessary but not sufficient to cover all ISRU objectives, at least for certain resources of interest.

Investigation Strategy 7A: ***Determine the concentration, mineralogic basis, and variation of water in Martian surface materials and identify associated chemical constituents that may negatively impact potential end-use processes of this water.***

In situ utilization processes require definition of the resources to influence equipment design and resource budgeting. Namely the form and concentration of water within the regolith is critical to this process. Resource sites with higher water content may drive the location of ISRU processes. With the focus on hydrated minerals for this sample opportunity (as opposed to subsurface ice), understanding the mineralogy will inform decisions about resource availability and possible byproducts. The water release profile upon heating (which stems from the hydration state and the type of hydrated minerals) is a critical engineering trade regarding heat input and the power profile of the hardware needed (Kleinhenz and Paz 2017). Potential contaminants that could release upon this heating could impact downstream systems, such as electrolysis, and necessitate the need for additional hardware to mitigate this.

The goal of the samples requested is to understand the water potential. "Typical" surface regolith, as defined in Abbud-Madrid et al. (2016), is likely to be of lower yield but more readily available. Consolidated material with a high water content may be more difficult to acquire and process, but the higher water yield could result reduced processing power (Fig. 7.4). A shallow subsurface sample of "typical" regolith may offer a slightly higher water yield than a surface sample. MSL DAN and REMS in situ results at Gale suggest the existence of an upper drier layer, 20 cm thick, involved in the water interchange with the atmosphere (with average 1.5–1.7% WEH) and a lower layer below 20 cm with higher water content (average 2.2–3.3% WEH) (Litvak et al. 2014; Mitrofanov et al. 2014; Martin-Torres et al. 2015). Orbital observations (Mitrofanov et al. 2004) also suggest a top dry layer of 2% water by mass overlying a wet layer with around 16% water by mass in some regions near the equator. Assuming *Viking 1* rocky sand, the thermal skin depth would be approximately 8 cm for the diurnal period and 2 m for the annual period (Paton et al. 2013). We recognize the potential challenges of obtaining a subsurface sample with the Mars 2020 mission. If the rover can get to depths greater than 8 cm, this would still provide a meaningful gradient for Earth analysis (Table 7.3).

Investigation Strategy 7B: ***Characterize the physical and thermophysical properties of Martian surface materials to influence the design of potential future ISRU surface systems and to develop high-fidelity simulant material for use in ISRU engineering test beds.***

The selection of technologies and techniques used to acquire and process the surface material will be highly dependent on the material properties themselves. All of this material property information can feed directly into ISRU system models to influence engineering design and can be used to generate/select high-fidelity simulant materials for use in hardware test programs.

Knowledge of physical properties will influence the selection of things like digging/excavation equipment (implement, force/energy required, life span of hardware, etc.) as well as material transfer equipment (gravity fed or mechanical conveyance, sizing, etc.). Reactor systems to extract water would also be dependent on physical and thermophysical properties. Thermal management and energy requirements are highly reliant on knowing thermal properties, while physical properties, such as particle size, would influence reaction mechanics. Knowledge of the surface fines or airborne dust components would impact filtration design, which is critical for seals and fluid lines as well as any catalyst materials (e.g., electrolysis or water purification units).

The most recent ISRU study focused on using the easily accessible granular surface material (Kleinhenz and Paz 2017), which is likely to have a low water yield. Consolidated material with potentially higher water

Table 7.3. Samples and measurements implied by Investigation Strategy 7A. Samples are listed in approximate priority order.

Samples identified to advance Investigation Strategy 7A:

- A "typical" regolith surface sample representative of abundant loose material.
- A subsurface regolith sample from the same location as above that accesses material isolated from diurnal heat cycling.
- At least one core sample of a sedimentary rock that displays the strongest signature of hydration in the exploration zone.

Note: The above three samples are identical to those requested for Investigation Strategy 7B. There is potential we can use the same sample for both purposes (as long as we do the measurements in the correct order).

- An additional regolith or rock samples to better constrain more fully the range or variability of water contents in the exploration zone.

Measurements identified to advance Investigation Strategy 7A:

- Identify hydrated minerals and hydration states in multiple samples of Martian regolith (to facilitate comparison between different regolith types) and in rock samples.
- Characterize the water release profile of these samples with temperature and identify associated contaminants released. Contaminants of particular interest are chlorides and perchlorates which are potential contaminants for water use (e.g., propellant production, life support), but are a potentially useful resource for closed loop life support applications.
- Sample probes of at least the depth of the thermal skin depth at sample location, whereby the temperature will remain roughly constant, to characterize the depth of the present-day active water layer (e.g., absorption and desorption on diurnal/seasonal time scales).

Table 7.4. Samples and measurements implied by Investigation Strategy 7B. Samples are listed in approximate priority order.

Samples identified to advance Investigation Strategy 7B:

- A "typical" regolith surface sample representative of abundant loose material.
- A subsurface regolith sample from the same location as the above that accesses material isolated from diurnal heat cycling.
- At least one core sample of a sedimentary rock interpreted to have a high concentration of hydrated minerals.

Note: The above three samples are identical to those requested in Investigation Strategy 7A. There is potential we can use the same material for both purposes (as long as we do the measurements in the correct order).

- An airborne dust sample preferably collected on a filter material to analyze airborne dust properties and its potential interactions with filter material.

Measurements identified to advance Investigation Strategy 7B:

- For Martian regolith, characterize the geotechnical properties such as regolith particle size distribution and shape, densities, and strength/cohesion properties. This information will influence simulant design and material handling technology (e.g., excavation and transfer).
- For (hydrated) rock samples, characterize the strength and other properties to understand excavation and comminution of rock materials.
- Characterize the thermal properties of the samples to understand heat transfer for resource extraction and system thermal management purposes.
- Analyze regolith properties that may be important for its use in construction applications including as a potential building or shielding material, or as a feed stock for additive manufacturing processes.
- Measure grain size distribution in regolith sample that are comprised of airfall dust in order to understand how small particles might damage catalyst function.

content may require more robust excavation and comminution equipment. However, engineering studies and models to trade this against the potential for higher water yield require specific geotechnical information of both the consolidated material as well as the granular surface material.

Samples are requested to help bound the range of these properties. The three required samples are identical to those requested in Investigation Strategy 7A. Understanding the potential water yield of a resource along with its physical properties enables important engineering trades (Table 7.4).

Investigation Strategy 7C: Identify components in Martian granular material that may be beneficial or detrimental to its use for in situ agriculture. (Also of interest to Objective 6)

Having multiple regolith samples for basic elemental analysis, and more traditional "soils" type analyses would be invaluable for understanding the needs of future Martian agriculture. This could include analyses of the mineral composition, cation exchange capacity (CEC), water holding and so-called matric potential, osmotic potential (from soluble compounds/salts), and porosity (Thompson and Troeh 1978). Of course, these must all be taken in the context that the Martian regolith is mixture of broken and weathered rock, and not a true "soil" (as that term is used connection with terrestrial agriculture), with organic matter, clay, silts, an active microbiome, and more. Elements essential for plants include (in approximate descending order of need): N, K, Ca, Mg, S, P, Fe, Mn, B, Cl, Zn, Cu, and Mo (Hoagland 1938; Epstein 1972). Other elements can help some plants according to some authors, such as Si, Ni, Co (for N-fixing plants); Na for

Fig. 7.5. Seedlings grown in regolith simulant amended soil as part of current NASA sponsored activities.

some halophytes; and perhaps a few others in very small quantities (Epstein 1972). On the other hand, high levels of some soluble elements, especially transition metals (e.g., Zn, Mn, Cu, Cr, Ni) (Moore et al. 2017) can often be toxic to plants, as can high levels of Na or B or soluble Al. In addition to the straight elemental composition, the compounds and minerals that contain these elements will be important to understand, since these will determine the availability as plant nutrients either through dissolution by water or through microbial processes (Fig. 7.5).

Basaltic sand dunes are very common on the Martian surface and represent a likely candidate for future Martian agriculture due to the fertility of basaltic soils on Earth. Initial analyses by the MSL rover of basaltic dunes in Gale Crater suggests these materials could be a good source of K, Ca, Mg, Fe, Mn, P, Zn, and Cu; however, they might be depleted in Cl, S, and N (Ehlmann et al. 2017). Fine-grained bright dune

Table 7.5. Samples and measurements implied by Investigation Strategy 7C. Samples are listed in approximate priority order.

Samples identified to advance Investigation Strategy 7C:
- A sample of sand-sized basaltic dune material.
- One sample of bright fine-grained dune material.
- An additional regolith sample from one or both of the locations specified above.

Measurements identified to advance Investigation Strategy 7C:
- Identify minerals that are high in elements typically used in fertilizer (N, P, K) in multiple samples of Martian regolith (to facilitate comparison between different regolith types).
- Identify compounds that could potentially be damaging to food crop production processes.
- Characterize the presence of metals that may be important for soil microbial metabolism.

materials on Mars have been shown to contain Cl, S, and N and therefore might be good sources for these elements for agriculture (Table 7.5).

***Investigation Strategy 7D:* Contingent on discovering significant concentrations of natural metallic resources, characterize the source materials to enable predictions of where and how such deposits may be concentrated on Mars.**

Because of their rarity, metal resources are arguably one of the two most highly valued resources for modern human civilization (energy resources being the other). As such, they always command extra attention when discovered, either deliberately or accidentally. Ore-forming processes on Earth happen when certain elements are segregated from others, typically either by differential transport or precipitation mechanisms. Once these mechanisms are understood, experts in mineral exploration can predict the location, grade, and mechanical consistency of natural concentrations (and hopefully, these concentrations exceed the definition of "ore"). In the exploration process, it is quite common to have low-grade halos of different kinds of minerals/elements around high-grade deposits—anomalous samples therefore can serve as important signposts.

On Mars we do not know that ore-forming processes took place the same way they did on Earth. However, because of the potential future value to the very long-range exploration/habitation of Mars, if samples with high concentrations of possible future Martian commodities are encountered, they should be sampled and studied in detail on Earth. The focus is on those metals considered to be the basic building blocks of technology and commerce (Fig. 7.6). Note, however, that we view this as being dependent on samples of opportunity. The chance of encountering something

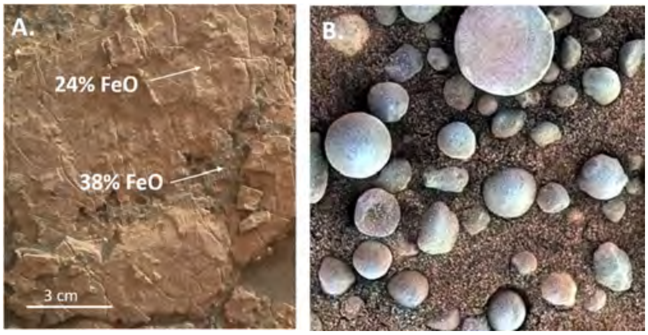

Fig. 7.6. Example of anomalous iron detection. A) MAHLI image of the APXS target "Morancy Stream" which has 38% FeO and "Morancy Stream Offset" (MSO) which has 24% FeO, acquired on Sol 1668 of the Curiosity rover mission. Image credit NASA/JPL/Caltech/MSSS. B) Small hematite spherules on the Martian surface near Fram Crater, visited by NASA's Mars Exploration Rover Opportunity during April 2004. The area shown is about 2 cm across. Image Credit: NASA/JPL-Caltech/Cornell/USGS

Table 7.6. Samples and measurements implied by Investigation Strategy 7D.

Samples identified to advance Investigation Strategy 7D:
• One sample of the ore-rich material.
• Additional samples of rock units nearby to better understand potential ore-forming processes.
Measurements identified to advance Investigation Strategy 7D:
• Identify minerals that are high in metals (such as Fe, Ni, Al, Cu, Cr, Au, PGM [Platinum Group Metals], KREEP [Potassium, Rare Earth Elements, Phosphorus]) in multiple samples of Martian regolith (to facilitate comparison between different regolith types).

significant is considered to be low, so it is not justified to have the rover spend a portion of its limited lifetime searching for this. However, if something meaningful is encountered, it could well be worth sampling (Table 7.6).

8 DISCUSSION

8.1 Will the Samples to Be Collected by M-2020 Be Worth Returning?

Can these objectives be achieved with the samples to be collected by M-2020 and by a potential retrieval mission?

The most important conclusion from this analysis is that the details of the science that can be achieved are highly dependent on the samples that are made available to the analysts on Earth. Although sample suites and sample context are important, there are multiple ways to put together the collection to achieve the objectives. The M-2020 rover is expected to be able to collect approximately 20 samples within its prime mission. In our view, a carefully chosen set of 20 samples is adequate enough to assemble a minimal necessary suite of samples and selected individual samples that will allow us to achieve the objectives we have proposed. These objectives can be more confidently achieved with a full set of 31 samples, as such a suite represents the broader diversity defined as necessary. This, however, would presumably require that M-2020 continue its sampling operations into the extended mission phase.

- **Objective 1.** All of the candidate landing sites for M-2020 have previously documented evidence for at least one of the four ancient geologic environments known from Earth analog studies to have high habitability potential and high potential for the preservation of biosignatures. We want to analyze samples from these environments to understand their geologic processes, and we need this foundation to carry out the detailed investigations associated with astrobiology and geochronology. It is possible/likely that more than one of these environments will be represented at each landing site. For example, all of the candidate sites have been exposed to weathering, the key attribute of Sub-Objective 1.4, and all have likely been exposed to ancient Martian groundwater, the key attribute of Sub-Objective 1.3. In addition to the above four, a fifth geologic environment, igneous terrane, is deemed important for the nonlife objectives of MSR. It may or may not be accessible in outcrop at all of these sites. However, as pointed out in Section 1.5, most of our scientific objectives related to igneous rocks do not require outcrop-sourced samples (i.e., in situ), but can make use of transported samples (i.e., ex situ). Our Mars lander and rover experience to date suggests that such samples exist nearly everywhere on Mars. It is also important to note that the landing sites currently under consideration are being selected and compared based on what can be seen from orbit. However, as has been shown by *Sojourner*, *Opportunity*, *Spirit*, and *Curiosity*, it is commonplace to discover things on the ground that were not visible from orbit. Thus, aspects of many or all of the five high-priority geologic environments may end up in the sample collection. It is also paramount that any samples to be collected are targeted with a view toward testing their biological potential to fit Objective 2.

- **Objective 2.** Given the samples collected as a part of Objective 1, and their adequacy to improve our understanding of Mars's biological potential we have in this objective developed a quite technical assessment and sets of protocols that are highly dependent on complex sample preparation, high-precision, low-detection limit analyses, and stringent contamination control procedures that are ideally suited to returned sample analysis.
- **Objective 3.** We would very much like to date one or more ancient surfaces that have a defined cratering density. All Martian landing sites offer cratered surfaces, and all of the landing sites under consideration by M-2020 are very old (Hesperian or Noachian). However, interpreting crater density can be complicated by the nature of the substrate, the possibility of resurfacing, and the effect of secondary craters, all of which can be interrogated by rovers and returned samples. In addition to that, however, each of the landing sites presents the opportunity to date the products of important Martian geologic processes.
- **Objective 4.** The essential strategies for this objective relate to collecting *and analyzing* samples of solid materials that have equilibrated with the ancient Martian atmosphere, and/or contain trapped gaseous/fluid inclusions of that atmosphere, and making measurements on one or more dedicated samples of the modern Martian atmosphere. A common feature across all the candidate landing sites is that there is abundant regolith and evidence at each site for ancient water/atmosphere–rock interactions. However, M-2020 is not designed to collect an atmospheric sample. This should be adopted as a requirement on the sample-retrieval mission.
- **Objective 5.** Understanding Mars as a system requires the collection of very old rocks, including at least some igneous rocks, and rocks (either sedimentary or igneous) that can be used to test models of the history of the Martian *paleomagnetic* field. All of the current candidate landing sites are in Mars' ancient geological terrane, although we cannot presently be sure that they will be suitable for paleomagnetic measurements.
- **Objective 6.** The primary samples of interest for understanding risks to possible future human missions to the Martian surface are different kinds of granular materials, including regolith and airfall dust. It is certain that M-2020 will be able to acquire these.
- **Objective 7.** For the purpose of ISRU, we are primarily interested in water-bearing mineral samples, and in regolith. M-2020 will also be able to acquire these.
- **Conclusion:** If the Mars 2020 rover acquires a scientifically well-chosen set of samples, with sufficient geological diversity, and if those samples were returned to Earth, then major progress can be expected on all seven of the objectives proposed in this study, regardless of the final choice of landing site. The specifics of which parts of Objective 1 could be achieved would be different at each of the final three candidate landing sites, but some combination of critically important progress could be made at any of them.

To answer the question in the heading of this section: **YES**

8.2 Summary of Sample Types of Interest for Returned Sample Analysis

A compilation of sample types described in the various sections of this report results in Table 8.1 for the rock samples and Table 8.2 for the granular material. In the case of the rock samples, the columns of Table 8.1 are organized by geological category, the first five of which are keyed to the geological environments being targeted. In Table 8.2, the columns represent the four objectives for which scientists could most make use of samples of granular materials—this will help summarize what kinds of samples of regolith are of interest. Since we do not yet know which landing site the M-2020 sample-collecting rover will be sent to, or where within the landing ellipse the actual landing will be, the sequence by which the samples described in these tables will be collected is indeterminate. However, considering what we know about the three landing sites under discussion, we are confident that regardless of where M-2020 starts its traverse, the rover will be able to collect at least a subset of the desired materials. It is our hope that the M-2020 science team will plan the productive lifetime of the rover to acquire as many of the kinds of samples described in these tables as possible.

Note that we cannot expect that M-2020 will be able to collect all the samples. Constraints will include topographic limitations on traverse planning, limitations on the geology available for sampling, a fixed and limited number of sample tubes, etc. Not forgetting, of course, that M-2020 has its own set of science and engineering objectives aside from sample collection and caching. A sample collection that justifies return, therefore, is not one that includes every sample described in these tables, but one that includes a reasonable subset (recognizing, of course, that what is reasonable to some people may not be reasonable to others). The authors of this report would especially like to see a minimum "returnable"

Table 8.1. Summary of rock samples desired/required to achieve the objectives of Mars Sample Return.

General Geological Category						
Sedimentary	**Hydrothermal**	**Deep subsurface**	**Subaerial**	**Igneous**	**Volatile-Bearing**	**Other**
A suite of sedimentary rocks representative of the stratigraphic section. A suite of sedimentary rocks showing a range of lithification intensity and style. Rocks of any type that show a range of weathering styles and weathering intensity, including weathering rinds, if present. Sedimentary rocks with a variety of grain compositions. Relatively coarse-grained clastic sedimentary rocks. Most valuable would be rocks for which at least some of the sedimentary grains are multi-mineralic (i.e., small rocks), and which could be studied independently. A suite of sedimentary rocks representative of stratigraphy within	A suite of hydrothermal samples and/or altered host rocks representing decreasing paleotemperature with distance (e.g., proximal to distal) from a hydrothermal vent A suite of hydrothermally generated deposits and/or hydrothermally altered host rocks representative of the range of chemistry and mineralogy within an ancient hydrothermal system. Hydrothermally generated/altered rocks sampling interbedding, crosscutting and/or overgrowth relationships from different stratal positions within the hydrothermal system A suite of	Mineralized fractures or ridges, diagenetic concretions, zones with color change indicating leaching and/or cements and should be sampled along with adjacent host rock. Cross-sectionally arranged samples from altered zones. Key phases include Fe and Mn oxides, phyllosilicates, silica, sulfates, carbonates, and other salts. Goal is to use samples to track fluid chemistry change with system time evolution or distance.	A suite of rocks or soils/paleosols representative of the range of depth and weathering, from most-altered to least-altered/unaltered parent material. Mineral deposits (e.g., iron oxides, salts, carbonates) precipitated in chemical gradients (e.g., springs) or due to evaporation (e.g., ephemeral ponds), especially those with evidence for long-term buildup. Rocks with precipitated coatings or rinds. Rocks formed under a variety of redox conditions, and especially those with evidence for sedimentation or mineral precipitation under reducing conditions.	A suite of igneous rocks as diverse in composition and texture as possible A suite of ancient rocks that are the most likely candidates for the original crust of Mars, including those subjected to the least amount of apparent aqueous alteration Igneous samples from an extensive lava flow in the >3.5 Ga and <1 Ga age ranges from surfaces for which well-determined cratering statistics have been established Basalts and highly fractionated rocks are especially informative. An ultramafic igneous rock within a basaltic igneous host rock that could represent a potential mantle or lower crustal xenolith.	Sedimentary rocks and regolith of known age containing clays or other hydrated minerals, in particular minerals that contain structural volatiles (carbonates, sulfates, sulfides, chlorides, perchlorates). Dry, clay-free dune material to study adsorption and dry implantation processes of atmospheric species in contrast to S8. Any rock of known age containing minerals with trapped fluid inclusions. Highly shocked rock containing impact melt pockets or veins, where the timing of the shock event is known.	Oriented samples of igneous or sedimentary rocks Samples, including impact melts, taken from individual craters amenable for age dating. Breccias associated with large basin-forming impacts Any rock of known age containing minerals with trapped fluid inclusions. Highly shocked rock containing impact melt pockets or veins, where the timing of the shock event is known. Hydrothermally altered impact breccia or in-place rocks modified by impact-induced hydrothermal activity; any impactite or heavily shocked rock of any type.

Table 8.1. *Continued*. Summary of rock samples desired/required to achieve the objectives of Mars Sample Return.

General Geological Category	
an ancient stream channel.	hydrothermally generated/altered rocks representative of the range of rocks fitting hypothesized age model within the potential hydrothermal system.
Sample(s) of lithified aeolian sedimentary rock (at different stratigraphic horizons).	Rocks, especially clays, that potentially show evidence of late-stage diagenetic processes such as hydrothermal alteration, superimposed on the hydrothermal system

Table 8.2. Summary of granular material samples desired/required to achieve the objectives of MSR.

General Intended Purpose			
Sedimentary System	***Volatiles***	***Environmental Hazards***	***ISRU***
Modern regolith, especially if locally derived. Sample of modern aeolian sediment from the surface.	Dust and soil/sediments including a perchlorate-bearing sample	Concentrated airfall dust Subsurface regolith, as deep as possible Dust on the surface-exposed sample tubes or hardware Near-surface/surface regolith containing dust-sized particles	Modern regolith, especially if locally derived. A subsurface regolith sample from the same location as a "typical" regolith surface sample that accesses material isolated from diurnal heat cycling Dust and soil/sediments including a perchlorate-bearing sample Sample of modern aeolian sediment from the surface. Martian airfall dust

sample collection be defined as one that allows at least some progress on each of the seven objectives proposed in this report. As sample collection and retrieval scenarios are further defined, clearly this will need more discussion.

8.3 Some Proposals for the Downstream Missions of a MSR Campaign

Our analysis has also identified some issues at different levels of priority that affect the downstream missions that would retrieve the samples and return them to Earth. These include the following:

- As discussed under Objective 4, one or more samples of modern atmospheric gas in containers significantly larger than the rock/regolith sample tubes would be scientifically quite valuable. The M-2020 mission is not designed to collect such samples. Our analysis indicates samples collected at two different time points in the Mars year for assessment of seasonal variability are of high priority to science. It should be possible to accommodate such atmospheric samples in the OS for return to Earth.
- Paleomagnetic measurements on returned samples are an important part of Objective 5, and a key sample quality criterion is ensuring that exposure to magnetic fields remains below 200 μT. Laboratory measurements of the magnetic field in drill actuators and the RIMFAX antenna on the M-2020 rover conducted by the Project fall well below this limit, so the decision was made not to include a magnetic witness blank in the sample containers. However, it is possible that the sample return missions could potentially expose the samples to higher magnetic fields and thus reduce the likelihood of making measurements of remnant magnetization in ancient Martian samples. It would be highly valuable to include a magnetic witness blank in the OS.
- As discussed above under Objective 6, there are reasons why samples of regolith/dust larger than could be collected by M-2020 alone would be valuable. A broader set of experiments would be possible, and we would have more confidence in the results. If it were possible to be able to collect additional regolith or dust sample mass from the SRL mission (perhaps as a contingency sample), it would be very valuable.
- Other issues relating to exposure of the sample tubes to high temperatures and/or pressures during return to Earth may be identified, once the mineralogy and nature of the cached samples is known.

Finding 6: The retrieval missions of a MSR campaign should (1) minimize stray magnetic fields to which the samples will be exposed and carry a magnetic witness plate to record exposure, (2) collect and return atmospheric gas sample(s), and (3) collect additional dust and/or regolith sample mass if possible.

8.4 Planning for the Management of the Samples Should They Be Transported to Earth

From this analysis, it would be possible to:

- compile a matrix of the analytical instruments/facilities and which investigations would require or desire them,
- evaluate which measurements or investigations can be carried out using sterilized samples—this may

become an important input into planning for the activities that must be carried out in containment either inside or outside of a Sample Receiving Facility,
- reconsider the amount of sample mass needed for each of the measurements, which may be an early input into a sample management plan; this has to include sample subdivision strategies, and sample allocation plans,
- reconsider how much of the sample collection would be allocated for scientific research "immediately," versus how much sample mass should be retained in pristine state for the benefit of future researchers.

8.5 Concluding Comments

We conclude that most/all of the seven objectives could be achieved if the Mars 2020 rover acquires, as expected, a scientifically well-chosen set of samples, and if those samples were returned to Earth. There are, of course, dependencies on the range of diversity within the sample collection (which will in turn be affected by several other unknowns, including how many samples are in the collection). With regard to Objective 1, the specific geologic processes that will be possible to characterize will depend on the selected landing site, and thus this represents a pivotal choice. However, it is evident that at least one of the critical sub-objectives of Objective 1, and likely more than one, would be possible with the Mars 2020 rover sample acquisition and caching activities, given the range of possible landing/sampling sites now under consideration.

We note that, as demonstrated by the Apollo lunar samples (e.g., Crawford 2012), returned Martian samples would be a resource for current and future generations of planetary scientists. Such samples offer not only the advantages of and potential of using a myriad of existing laboratory analytical techniques but also the promise of advances in analysis technologies that postdate sample return.

We conclude that it is important for the potential sample-retrieval missions to proceed as soon as possible after M-2020 has collected and cached the samples, both on scientific and on technical grounds. Scientifically, the exploration of Mars is a complex iteration of discovery and discovery response. There is more than one way to unravel the scientific puzzle that is Mars, but since results from earlier missions inform results from later missions, logical sequential relationships are important. It is widely accepted within the science community (e.g., witness the recent Decadal Survey) that the definitive answers from returned Mars samples would be the most important next thing. The potentially groundbreaking discoveries from MSR would assuredly generate fundamental knowledge and capabilities that will have long-lasting implications for both science and engineering. Second, the retrieval missions would likely either require, or greatly benefit from, existing Mars orbital telecommunications infrastructure. That infrastructure is aging, and the longer we wait to implement a sample return campaign, the higher the risk. While there are plans for refreshing this aging telecoms structure, it is by no means assured that the level of capability necessary to manage the risks of MSR will be available to ensure campaign success. Finally, there are potential negative effects to having the samples sitting un-retrieved on the Martian surface for a very long time. These could include having them be in a somewhat different thermal environment, which may trigger temperature-dependent reactions between the various components of the samples. Fortunately, rocks and minerals are relatively stable entities, so this is believed to be a relatively minor concern, and time frames up to a decade or more have previously been deemed to be acceptable—however, for samples of this quality and cost, we want the best we can get.

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A parallel PPT file to accompany this report has been prepared, and it may be accessed at https://mepag.jpl.nasa.gov/reports/iMOST%20presentation%20package.pptx. In case of discrepancies between the PPT and text versions of this analysis, the text version (this document) should be interpreted as superior.

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REFERENCES

Abbey W. J., Bhartia R., Beegle L. W., DeFlores L., Paez V., Sijapati K., Sijapati S., Williford K., Tuite M., Hug W., and Reid R. 2017. Deep UV Raman spectroscopy for planetary exploration: The search for in situ organics. *Icarus* 290:201–214. https://doi.org/10.1016/j.icarus.2017.01.039.

Abbud-Madrid A., Beaty D. W., Boucher D., Bussey B., Davis R., Gertsch L., Hays L. E., Kleinhenz J., Meyer M., Moats M., Mueller R., Paz A., Suzuki N., Van Susante P., Whetsel C., and Zbinden E. A. 2016. Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study. http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

Abrajano T. A., Sturchio N. C., Kennedy B. M., Lyon G. L., Muehlenbachs K., and Bohlke J. K. 1990. Geochemistry of reduced gas related to serpentinization of the Zambales ophiolite, Philippines. *Applied Geochemistry* 5:625–630. https://doi.org/10.1016/0883-2927(90)90060-I.

Abramov O. and Mojzsis S. J. 2009. Microbial habitability of the Hadean Earth during the late heavy bombardment. *Nature* 459:419–422. https://doi.org/10.1038/nature08015.

Ackiss S. E., Horgan B., Campbell A., Seelos F. P., Farrand W. H., and Wray J. J. 2016. Mineralogical evidence for subglacial volcanoes in the Sisyphi Montes region of Mars. In *Sixth International Conference on Mars Polar Science and Exploration* (abstract #1926).

Acuña M. H., Kletetschka G., and Connerney J. E. P. 2008. Mars' crustal magnetization: A window into the past. In *The Martian surface*, edited by Bell J. Cambridge, UK: Cambridge University Press. pp. 242–262. https://doi.org/10.1017/cbo9780511536076.012

Adcock C. T., Udry A., Hausrath E. M., and Tschauner O. 2018. Craters of the Moon National Monument basalts as unshocked compositional and weathering analogs for Martian rocks and meteorites. *American Mineralogist* 103:502–516. https://doi.org/10.2138/am-2018-6193.

Aerts J., Röling W., Elsaesser A., and Ehrenfreund P. 2014. Biota and biomolecules in extreme environments on Earth: Implications for life detection on Mars. *Life* 4:535–565. https://doi.org/10.3390/life4040535.

Agee C. B., Wilson N. V, McCubbin F. M., Ziegler K., Polyak V. J., Sharp Z. D., Asmerom Y., Nunn M. H., Shaheen R., Thiemens M. H., Steele A., Fogel M. L., Bowden R., Glamoclija M., Zhang Z., and Elardo S. M. 2013. Unique meteorite from early Amazonian Mars: Water-rich basaltic breccia Northwest Africa 7034. *Science* 339:780–785. https://doi.org/10.1126/science.1228858

Allen C. C. and Oehler D. Z. 2008. A case for ancient springs in Arabia Terra, Mars. *Astrobiology* 8:1093–1112. https://doi.org/10.1089/ast.2008.0239.

Allen C. C., Allton J., Lofgren G., Righter K., and Zolensky M. 2011. Curating NASA's extraterrestrial samples—Past, present, and future. *Chemie Der Erde—Geochemistry* 71:1–20. https://doi.org/10.1016/J.CHEMER.2010.12.003.

Allen P. A. 2008. From landscapes into geological history. *Nature* 451:274–276. https://doi.org/10.1038/nature06586.

Allwood A., Beaty D., Bass D., Conley C., Kminek G., Race M., Vance S., and Westall F. 2013. Conference summary: Life detection in extraterrestrial samples. *Astrobiology* 13:203–216. https://doi.org/10.1089/ast.2012.0931.

Amundson R., Ewing S., Dietrich W., Sutter B., Owen J., Chadwick O., Nishiizumi K., Walvoord M., and McKay C. 2008. On the in situ aqueous alteration of soils on Mars. *Geochimica et Cosmochimica Acta* 72:3845–3864. https://doi.org/10.1016/J.GCA.2008.04.038.

Andersen D. T., Sumner D. Y., Hawes I., Webster-Brown J., and Mckay C. P. 2011. Discovery of large conical stromatolites in Lake Untersee, Antarctica. *Geobiology* 9:280–293. https://doi.org/10.1111/j.1472-4669.2011.00279.x.

Andersen D. W., Wharton R. A., and Squyres S. W. 1993. Terrigenous clastic sedimentation in Antarctic dry valley lakes. *Physical and biogeochemical processes in Antarctic Lakes*. Washington, D.C.: American Geophysical Union (AGU). pp. 71–81. https://doi.org/10.1029/ar059p0071

Anderson T. F., Donnelly T. W., Drever J. I., Eslinger E., Gieskes J. M., Kastner M., Lawrence J. R., and Perry E. A. 1976. Geochemistry and diagenesis of deep-sea sediments from leg 35 of the Deep Sea Drilling Project. *Nature* 261:473–476. https://doi.org/10.1038/261473a0.

Andrews-Hanna J. C. and Lewis K. W. 2011. Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs. *Journal of Geophysical Research* 116: E02007. https://doi.org/10.1029/2010je003709

Andrews-Hanna J. C., Phillips R. J., and Zuber M. T. 2007. Meridiani Planum and the global hydrology of Mars. *Nature* 446:163–166. https://doi.org/10.1038/nature05594.

Ansan V., Loizeau D., Mangold N., Le Mouélic S., Carter J., Poulet F., Dromart G., Lucas A., Bibring J.-P., Gendrin A., Gondet B., Langevin Y., Masson P., Murchie S., Mustard J. F., and Neukum G. 2011. Stratigraphy, mineralogy, and origin of layered deposits inside Terby Crater, Mars. *Icarus* 211:273–304. https://doi.org/10.1016/J.ICARUS.2010.09.011.

Armstrong A. E. and Collins M. 1969. NASA JSC, 81.

Arvidson R. E., Bell J. F., Bellutta P., Cabrol N. A., Catalano J. G., Cohen J., Crumpler L. S., Des Marais D. J., Estlin T. A., Farrand W. H., Gellert R., Grant J. A., Greenberger R. N., Guinness E. A., Herkenhoff K. E., Herman J. A., Iagnemma K. D., Johnson J. R., Klingelhöfer G., Li R., Lichtenberg K. A., Maxwell S. A., Ming D. W., Morris R. V., Rice M. S., Ruff S. W., Shaw A., Siebach K. L., De Souza P. A., Stroupe A. W., Squyres S. W., Sullivan R. J., Talley K. P., Townsend J. A., Wang A., Wright J. R., and Yen A. S. 2010. Spirit Mars Rover Mission: Overview and selected results from the northern Home Plate Winter Haven to the side of Scamander crater. *Journal of Geophysical Research* 115: E00F03. https://doi.org/10.1029/2010je003633

Atreya S. K., Trainer M. G., Franz H. B., Wong M. H., Manning H. L. K., Malespin C. A., Mahaffy P. R., Conrad P. G., Brunner A. E., Leshin L. A., Jones J. H., Webster C. R., Owen T. C., Pepin R. O., and Navarro-González R. 2013. Primordial argon isotope fractionation in the atmosphere of Mars measured by the SAM instrument on *Curiosity* and implications for atmospheric loss. *Geophysical Research Letters* 40:5605–5609. https://doi.org/10.1002/2013GL057763.

Atreya S. K., Wilson E., Encrenaz T., Kaiser R., and Mahaffy P. 2017. Coupled surface-atmosphere chemistry of the Martian peroxide and perchlorate oxidants. In *19th EGU General Assembly, EGU2017*. 3784 p.

Aubrey A., Cleaves H. J., Chalmers J. H., Skelley A. M., Mathies R. A., Grunthaner F. J., Ehrenfreund P., and Bada J. L. 2006. Sulfate minerals and organic compounds on Mars. *Geology* 34:357. https://doi.org/10.1130/G22316.1.

Avice G., Marty B., Burgess R., Hofmann A., Philippot P., Zahnle K., and Zakharov D. 2018. Evolution of atmospheric xenon and other noble gases inferred from Archean to Paleoproterozoic rocks. *Geochimica et Cosmochimica Acta* 232:82–100. https://doi.org/10.1016/J.GCA.2018.04.018.

Bada J. L. and McDonald G. D. 1996. Detecting amino acids on Mars. *Analytical Chemistry* 68:668A–673A. https://doi.org/10.1021/ac9621231.

Bakermans C., Skidmore M. L., Douglas S., and McKay C. P. 2014. Molecular characterization of bacteria from permafrost of the Taylor Valley, Antarctica. *FEMS Microbiology Ecology* 89:331–346. https://doi.org/10.1111/1574-6941.12310.

Bandfield J. L., Edwards C. S., Montgomery D. R., and Brand B. D. 2013. The dual nature of the Martian crust: Young lavas and old clastic materials. *Icarus* 222:188–199. https://doi.org/10.1016/J.ICARUS.2012.10.023.

Banham S. G., Gupta S., Rubin D. M., Watkins J. A., Sumner D. Y., Grotzinger J. P., Lewis K. W., Edgett K. S., Edgar L. A., Stack K. M., Bell J. F., Day M. D., Ewing R. C., and Laporte M. P. 2017. The Stimson formation: Determining the morphology of a dry aeolian dune system and its climatic significance in Gale crater (abstract #2014). 48th Lunar and Planetary Science Conference. CD-ROM.

Baratoux D., Toplis M. J., Monnereau M., and Gasnault O. 2011. Thermal history of Mars inferred from orbital geochemistry of volcanic provinces. *Nature* 472:338–341. https://doi.org/10.1038/nature09903.

Barnes I. and O'Neil J. R. 1969. The relationship between fluids in some fresh alpine-type ultramafics and possible modern serpentinization, Western United States. *GSA Bulletin* 80:1947–1960. https://doi.org/10.1130/0016-7606(1969) 80[1947:trbfis]2.0.co;2.

Barnes J. D. and Sharp Z. D. 2017. Chlorine isotope geochemistry. *Reviews in Mineralogy and Geochemistry* 82:345–378. https://doi.org/10.2138/rmg.2017.82.9.

Bass D. S. and Beaty D. W. 2011. Modern Martian habitability—Some planning questions associated with Mars sample return. In *The International Conference: Exploring Mars Habitability*, Lisbon, Portugal. 68 p. http://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=48911

Bass D. S., Beaty D. W., Carr M. H., Drake B. G., Hoffman S. J., and the MEPAG-SBAG P-SAG Team. 2012. The importance of MSR as a precursor to the future human exploration of Mars. In *75th Annual Meeting of the Meteoritical Society*, Cairns, Australia, (abstract #5400), www.lpi.usra.edu/meetings/metsoc2012/pdf/5400.pdf.

Baumeister J. L., Hausrath E. M., Olsen A. A., Tschauner O., Adcock C. T., and Metcalf R. V. 2015. Biogeochemical weathering of serpentinites: An examination of incipient dissolution affecting serpentine soil formation. *Applied Geochemistry* 54:74–84. https://doi.org/10.1016/J.APGEOCHEM.2015.01.002.

Beard B. L., Johnson C. M., Cox L., Sun H., Nealson K. H., and Aguilar C. 1999. Iron isotope biosignatures *Science* 285:1889–1892. https://doi.org/10.1126/science.285.5435.1889

Beaty D. W., Grady M. M., and iMARS Working Group. 2008. Preliminary planning for an International Mars Sample Return Mission: Report of the International Mars Architecture for the Return of Samples (iMARS) Working Group. https://mepag.jpl.nasa.gov/reports/iMARS_FinalReport.pdf

Beaty D. W., Liu Y., Des Marais D. J, Borg L. E., Herd C. D. K., McLennan S. M., Allen C. C., Bass D. S., Farley K. A., and Mattingly R. L. 2014. Mars returned sample science: Scientific planning related to sample quality. In *8th International Mars Conference* (abstract # 1208).

Beaty D. W., Hays L. E., Williford K., and Farley K. 2015. Sample science input to landing site selection for Mars

2020: An in-situ exploration and sample caching rover. In *78th Annual Meeting of the Meteoritical Society* (abstract #1856). Where to cite this?

Beaty D. W., McSween H. Y., and Returned Sample Science Board (RSSB). 2016. Recommended maximum temperature for Mars returned samples (abstract #2662). 47th Lunar and Planetary Science Conference. CD-ROM.

Beaty D. W., Sefton-Nash E., Grady M. M., Carrier B. L., and McSween H. Y. 2018a. The potential scientific value of returned Martian samples: The 2018 iMOST Study. In 42nd COSPAR Scientific Assembly (abstract #B4.2-0010-2018). https://www.cospar-assembly.org/abstractcd/COSPAR-18/abstracts/B4.2-0010-18.pdf

Beaty D. W., Vijendran S., Edwards C. D., Meyer M. A., Carrier B. L., Grady M. M., McSween H. Y., and Sefton-Nash E. 2018b. Mars sample return—A proposed mission campaign whose time is now. In *81st Annual Meeting of The Meteoritical Society* (abstract #6344).

Beegle L., Bhartia R., White M., , De Flores L., , Abbey W., , Wu Y-H., Cameron B., Moore J., Fries M., Burton A. S., Edgett K. S., Ravine M. A., Hug W. F., Reid R., Nelson T., Clegg S., Weins R., Asher S. A., Sobron P., and the SHERLOC Science Team. 2015. SHERLOC: Scanning habitable environments with Raman & luminescence for organics & chemicals. In *2015 IEEE Aerospace Conference*. pp. 1–11. IEEE. https://doi.org/10.1109/aero.2015.7119105

Benison K. C. and Bowen B. B. 2006. Acid saline lake systems give clues about past environments and the search for life on Mars. *Icarus* 183:225–229. https://doi.org/10.1016/J.ICARUS.2006.02.018.

Benison K. C. and LaClair D. A. 2003. Modern and ancient extremely acid saline deposits: Terrestrial analogs for Martian environments? *Astrobiology* 3:609–618. https://doi.org/10.1089/153110703322610690.

Benison K. C., Bowen B. B., Oboh-Ikuenobe F. E., Jagniecki E. A., LaClair D. A., Story S. L., Mormile M. R., and Hong B.-Y. 2007. Sedimentology of acid saline lakes in Southern Western Australia: Newly described processes and products of an extreme environment. *Journal of Sedimentary Research* 77:366–388. https://doi.org/10.2110/jsr.2007.038.

Berger J. A., Schmidt M. E., Gellert R., Boyd N. I., Desouza E. D., Flemming R. L., Izawa M. R. M., Ming D. W., Perett G. M., Rampe E. B., Thompson L., Van Bommel S., and Yen A. S. 2017. Zinc and germanium in the sedimentary rocks of Gale Crater on Mars indicate hydrothermal enrichment followed by diagenetic fractionation. *Journal of Geophysical Research: Planets* 122:1747–1772. https://doi.org/10.1002/2017JE005290.

Bertka C. M. and Fei Y. 1997. Mineralogy of the Martian interior up to core-mantle boundary pressures. *Journal of Geophysical Research: Solid Earth* 102:5251–5264. https://doi.org/10.1029/96JB03270.

Bhardwaj A., Sam L., Martín-Torres F. J., Zorzano M.-P., and Fonseca R. M. 2017. Martian slope streaks as plausible indicators of transient water activity. *Scientific Reports* 7:7074. https://doi.org/10.1038/s41598-017-07453-9.

Bhatia M. R. 1983. Plate tectonics and geochemical composition of sandstones. *The Journal of Geology* 91:6. https://doi.org/10.2307/30064711

Bibring J.-P., Langevin Y., Mustard J. F., Poulet F., Arvidson R., Gendrin A., Gondet B., Mangold N., Pinet P., Forget F., Berthé M., Bibring J. P., Gendrin A., Gomez C., Gondet B., Jouglet D., Poulet F., Soufflot A., Vincendon M., Combes M., Drossart P., Encrenaz T., Fouchet T., Merchiorri R., Belluci G., Altieri F., Formisano V., Capaccioni F., Cerroni P., Coradini A., Fonti S., Korablev O., Kottsov V., Ignatiev N., Moroz V., Titov D., Zasova L., Loiseau D., Mangold N., Pinet P., Douté S., Schmitt B., Sotin C., Hauber E., Hoffmann H., Jaumann R., Keller U., Arvidson R., Mustard J. F., Duxbury T., Forget F., and Neukum G. 2006. Global mineralogical and aqueous mars history derived from OMEGA/Mars Express data. *Science* 312:400–404. https://doi.org/10.1126/science.1122659

Bidle K. D., Lee S., Marchant D. R., and Falkowski P. G. 2007. Fossil genes and microbes in the oldest ice on earth. *Proceedings of the National Academy of Sciences* 104:13,455–13,460. https://doi.org/10.1073/pnas.0702196104.

Biemann K., Oro J., Toulmin P., Orgel L. E., Nier A. O., Anderson D. M., Simmonds P. G., Flory D., Diaz A. V., Rushneck D. R., Biller J. E., and Lafleur A. L. 1977. The search for organic substances and inorganic volatile compounds in the surface of Mars. *Journal of Geophysical Research* 82:4641–4658. https://doi.org/10.1029/JS082i028p04641.

Bishop J. L. and Englert P. A. J. 2016. Antarctic Dry valley sediments as analogs for microbial systems in a cold mars-like environment. In *Biosignature preservation and detection in Mars analog environments* (abstract #2017).

Bishop J. L. and Murad E. 2002. Spectroscopic and geochemical analyses of ferrihydrite from springs in Iceland and applications to Mars. *Geological Society, London, Special Publications* 202:357–370. https://doi.org/10.1144/GSL.SP.2002.202.01.18.

Bishop J. L. and Rampe E. B. 2016. Evidence for a changing Martian climate from the mineralogy at Mawrth Vallis. *Earth and Planetary Science Letters* 448:42–48. https://doi.org/10.1016/J.EPSL.2016.04.031.

Bishop J. L., Murad E., Lane M. D., and Mancinelli R. L. 2004. Multiple techniques for mineral identification on Mars: A study of hydrothermal rocks as potential analogues for astrobiology sites on Mars. *Icarus* 169:311–323. https://doi.org/10.1016/J.ICARUS.2003.12.025.

Bishop J. L., Dobrea E. Z. N., McKeown N. K., Parente M., Ehlmann B. L., Michalski J. R., Milliken R. E., Poulet F., Swayze G. A., Mustard J. F., Murchie S. L., and Bibring J.-P. 2008. Phyllosilicate diversity and past aqueous activity revealed at Mawrth Vallis, Mars. *Science* 321:830–833. https://doi.org/10.1126/science.1159699

Bishop J. L., Schelble R. T., McKay C. P., Brown A. J., and Perry K. A. 2011. Carbonate rocks in the Mojave Desert as an analogue for Martian carbonates. *International Journal of Astrobiology* 10:349–358. https://doi.org/10.1017/S1473550411000206.

Bishop J. L., Loizeau D., McKeown N. K., Saper L., Dyar M. D., Des Marais D. J., Parente M., and Murchie S. L. 2013. What the ancient phyllosilicates at Mawrth Vallis can tell us about possible habitability on early Mars. *Planetary and Space Science* 86:130–149. https://doi.org/10.1016/J.PSS.2013.05.006.

Bishop J. L., Englert P. A. J., Patel S., Tirsch D., Roy A. J., Koeberl C., Böttger U., Hanke F., and Jaumann R. 2014. Mineralogical analyses of surface sediments in the Antarctic Dry Valleys: Coordinated analyses of Raman spectra, reflectance spectra and elemental abundances. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering*

Sciences 372:20140198. https://doi.org/10.1098/rsta.2014.0198.

Bishop J. L., Fairén A. G., Michalski J. R., Gago-Duport L., Baker L. L., Velbel M. A., Gross C., and Rampe E. B. 2018. Surface clay formation during short-term warmer and wetter conditions on a largely cold ancient Mars. *Nature Astronomy* 2:206–213. https://doi.org/10.1038/s41550-017-0377-9.

Borg L. E. and Draper D. S. 2003. A petrogenetic model for the origin and compositional variation of the Martian basaltic meteorites. *Meteoritics & Planetary Science* 38:1713–1731. https://doi.org/10.1111/j.1945-5100.2003.tb00011.x.

Borg L. E., Brennecka G. A., and Symes S. J. K. 2016. Accretion timescale and impact history of Mars deduced from the isotopic systematics of Martian meteorites. *Geochimica et Cosmochimica Acta* 175:150–167. https://doi.org/10.1016/j.gca.2015.12.002.

Bosak T., Knoll A. H., and Petroff A. P. 2013. The meaning of stromatolites. *Annual Review of Earth and Planetary Sciences* 41:21–44. https://doi.org/10.1146/annurev-earth-042711-105327.

Boston P. J., Ivanov M. V., and McKay C. P. 1992. On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. *Icarus* 95:300–308.

Bouley S., Baratoux D., Matsuyama I., Forget F., Séjourné A., Turbet M., and Costard F. 2016. Late Tharsis formation and implications for early Mars. *Nature* 531:344–347. https://doi.org/10.1038/nature17171.

Bouvier L. C., Costa M. M., Connelly J. N., Jensen N. K., Wielandt D., Storey M., Nemchin A. A., Whitehouse M. J., Snape J. F., Bellucci J. J., Moynier F., Agranier A., Gueguen B., Schönbächler M., and Bizzarro M. 2018. Evidence for extremely rapid magma ocean crystallization and crust formation on Mars. *Nature* 558:586–589. https://doi.org/10.1038/s41586-018-0222-z.

Boynton W. V., Feldman W. C., Squyres S. W., Prettyman T. H., Bruckner J., Evans L. G., Reedy R. C., Starr R., Arnold J. R., Drake D. M., Englert P. A., Metzger A. E., Mitrofanov I., Trombka J. I., D'Uston C., Wanke H., Gasnault O., Hamara D. K., Janes D. M., Marcialis R. L., Maurice S., Mikheeva I., Taylor G. J., Tokar R., and Shinohara C. 2002. Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. *Science* 297:81–85. https://doi.org/10.1126/science.1073722

Boynton W. V., Taylor G. J., Evans L. G., Reedy R. C., Starr R., Janes D. M., Kerry K. E., Drake D. M., Kim K. J., Williams R. M. S., Crombie M. K., Dohm J. M., Baker V., Metzger A. E., Karunatillake S., Keller J. M., Newsom H. E., Arnold J. R., Brückner J., Englert P. A. J., Gasnault O., Sprague A. L., Mitrofanov I., Squyres S. W., Trombka J. I., d'Uston L., Wänke H., and Hamara D. K. 2007. Concentration of H, Si, Cl, K, Fe, and Th in the low- and mid-latitude regions of Mars. *Journal of Geophysical Research* 112:E12S99. https://doi.org/10.1029/2007je002887

Braakman R. and Smith E. 2012. The emergence and early evolution of biological carbon-fixation. *PLoS Computational Biology* 8:e1002455. https://doi.org/10.1371/journal.pcbi.1002455.

Bramble M. S., Mustard J. F., and Salvatore M. R. 2017. The geological history of Northeast Syrtis Major, Mars. *Icarus* 293:66–93. https://doi.org/10.1016/J.ICARUS.2017.03.030.

Brandon A. D., Puchtel I. S., Walker R. J., Day J. M. D., Irving A. J., and Taylor L. A. 2012. Evolution of the Martian mantle inferred from the 187Re–187Os isotope and highly siderophile element abundance systematics of shergottite meteorites. *Geochimica et Cosmochimica Acta* 76:206–235. https://doi.org/10.1016/J.GCA.2011.09.047.

Brantley S., White T. S., White A. F., Sparks D., Richter D., Pregitzer K., Derry L., Chorover J., Chadwick O., April R., Anderson S., and Amundson R. 2006. Frontiers in Exploration of the Critical Zone: Report of a workshop sponsored by the National Science Foundation (NSF), October 24-26, 2005. Newark, Delaware. http://criticalzone.org/national/publications/pub/brantley-et-al-2006-frontiers-in-exploration-of-the-critical-zone-report-of/

Brasier M. D., Green O. R., Jephcoat A. P., Kleppe A. K., Van Kranendonk M. J., Lindsay J. F., Steele A., and Grassineau N. V. 2002. Questioning the evidence for Earth's oldest fossils. *Nature* 416:76–81. https://doi.org/10.1038/416076a.

Brasier M. D., Green O. R., Lindsay J. F., McLoughlin N., Steele A., and Stoakes C. 2005. Critical testing of Earth's oldest putative fossil assemblage from the ~3.5 Ga Apex chert, Chinaman Creek, Western Australia. *Precambrian Research*, 140:55–102. https://doi.org/10.1016/j.precamres.2005.06.008

Bridges J. C., Catling D. C., Saxton J. M., Swindle T. D., Lyon I. C., and Grady M. M. 2001. Alteration assemblages in Martian Meteorites: Implications for near-surface processes. *Space Science Reviews* 96:365–392. https://doi.org/10.1023/A:1011965826553.

Bridges N. T. and Ehlmann B. L. 2018. The Mars Science Laboratory (MSL) Bagnold Dunes Campaign, Phase I: Overview and introduction to the special issue. *Journal of Geophysical Research: Planets* 123:3–19. https://doi.org/10.1002/2017JE005401.

Bridges N. T., Crisp J. A., and Bell J. F. 2001. Characteristics of the Pathfinder APXS sites: Implications for the composition of Martian rocks and soils. *Journal of Geophysical Research: Planets* 106:14,621–14,665. https://doi.org/10.1029/2000JE001393.

Bristow T. F., Bish D. L., Vaniman D. T., Morris R. V., Blake D. F., Grotzinger J. P., Rampe E. B., Crisp J. A., Achilles C. N., Ming D. W., Ehlmann B. L., King P. L., Bridges J. C., Eigenbrode J. L., Sumner D. Y., Chipera S. J., Moorokian J. M., Treiman A. H., Morrison S. M., Downs R. T., Farmer J. D., Marais D. D., Sarrazin P., Floyd M. M., Mischna M. A., and McAdam A. C. 2015. The origin and implications of clay minerals from Yellowknife Bay, Gale crater, Mars. *American Mineralogist* 100:824–836. https://doi.org/10.2138/am-2015-5077CCBYNCND.

Bristow T. F., Haberle R. M., Blake D. F., Des Marais D. J., Eigenbrode J. L., Fairén A. G., Grotzinger J. P., Stack K. M., Mischna M. A., Rampe E. B., Siebach K. L., Sutter B., Vaniman D. T., and Vasavada A. R. 2017. Low Hesperian PCO2 constrained from in situ mineralogical analysis at Gale Crater, Mars. *Proceedings of the National Academy of Sciences* 114:2166–2170. https://doi.org/10.1073/pnas.1616649114.

Brocks J. J. and Summons R. E. 2003. *Sedimentary hydrocarbons, biomarkers for early life*. Treatise on Geochemistry. Amsterdam: Elsevier. pp. 63–115. https://doi.org/10.1016/b0-08-043751-6/08127-5

Burkhardt C., Borg L. E., Brennecka G. A., Shollenberger Q. R., Dauphas N., and Kleine T. 2016. A nucleosynthetic origin for the Earth's anomalous ^{142}Nd composition. *Nature* 537:394–398. https://doi.org/10.1038/nature18956.

Burton Z. F. M., Bishop J. L., Englert P., Koeberl C., and Gibson E. 2018. Chemically active horizon in a soil pit from an intermittent pond site in the Dry Valleys Region, Antarctica and implications for soil processes on Mars (abstract #1086). 49th Lunar and Planetary Science Conference. CD-ROM.

Cabrol N. A. and Grin E. A. 1999. Distribution, classification, and ages of Martian impact crater lakes. *Icarus* 142:160–172. https://doi.org/10.1006/ICAR.1999.6191.

Cabrol N. A., Grin E. A., Cabrol N. A., and Grin E. A. 2010. Searching for lakes on Mars. In *Lakes on Mars*. Amsterdam: Elsevier. pp. 1–29. https://doi.org/10.1016/b978-0-444-52854-4.00001-5

Cain J. R. 2010. Lunar dust: The hazard and astronaut exposure risks. *Earth, Moon, and Planets* 107:107–125. https://doi.org/10.1007/s11038-010-9365-0.

Callahan M. P., Burton A. S., Elsila J. E., Baker E. M., Smith K. E., Glavin D. P., and Dworkin J. P. 2013. A search for amino acids and nucleobases in the Martian meteorite Roberts Massif 04262 using liquid chromatography-mass spectrometry. *Meteoritics & Planetary Science* 48:786–795. https://doi.org/10.1111/maps.12103.

Campbell K. A., Guido D. M., Gautret P., Foucher F., Ramboz C., and Westall F. 2015a. Geyserite in hot-spring siliceous sinter: Window on Earth's hottest terrestrial (paleo)environment and its extreme life. *Earth-Science Reviews* 148:44–64. https://doi.org/10.1016/J.EARSCIREV.2015.05.009.

Campbell K. A., Lynne B. Y., Handley K. M., Jordan S., Farmer J. D., Guido D. M., Foucher F., Turner S., and Perry R. S. 2015b. Tracing biosignature preservation of geothermally silicified microbial textures into the geological record. *Astrobiology* 15:858–882. https://doi.org/10.1089/ast.2015.1307.

Campbell K. A., Guido D. M., Vikre P. G., John D. A., Rhys D., and Hamilton A. 2018. The Miocene Atastra Creek sinter (Bodie Hills volcanic field, eastern California): 4D evolution of a geomorphically intact siliceous hot-spring deposit. *Journal of Volcanology and Geothermal Research*. https://doi.org/10.1016/j.jvolgeores.2018.12.006

Cannon K. M., Parman S. W., and Mustard J. F. 2017. Primordial clays on Mars formed beneath a steam or supercritical atmosphere. *Nature* 552:88–91. https://doi.org/10.1038/nature24657.

Carr M. H. and Head J. W. 2010. Geologic history of Mars. *Earth and Planetary Science Letters* 294:185–203. https://doi.org/10.1016/j.epsl.2009.06.042.

Carrier B. L. and Kounaves S. P. 2015. The origins of perchlorate in the Martian soil. *Geophysical Research Letters* 42:3739–3745. https://doi.org/10.1002/2015GL064290.

Carrier B. L., Beaty D. W., and Hecht M. H. 2017a. The potential value of returning samples of Martian dust and other granular materials for analysis in earth laboratories to preparing for the human exploration of Mars. In *Dust in the Atmosphere of Mars and Its Impact on Human Exploration* (abstract #6037).

Carrier B. L., Beaty D. W., Hecht M. H., and Liu Y. 2017b. Planning for the scientific use of samples of Martian granular materials potentially to be returned by Mars sample return. In *80th Annual Meeting of the Meteoritical Society* (abstract #6292).

Carrozzo F. G., Di Achille G., Salese F., Altieri F., and Bellucci G. 2017. Geology and mineralogy of the Auki Crater, Tyrrhena Terra, Mars: A possible post impact-induced hydrothermal system. *Icarus* 281:228–239. https://doi.org/10.1016/J.ICARUS.2016.09.001.

Carter J., Poulet F., Bibring J.-P., Mangold N., and Murchie S. 2013. Hydrous minerals on Mars as seen by the CRISM and OMEGA imaging spectrometers: Updated global view. *Journal of Geophysical Research: Planets* 118:831–858. https://doi.org/10.1029/2012JE004145.

Carter J., Loizeau D., Mangold N., Poulet F., and Bibring J.-P. 2015. Widespread surface weathering on early Mars: A case for a warmer and wetter climate. *Icarus* 248:373–382. https://doi.org/10.1016/J.ICARUS.2014.11.011.

Cartwright J. A., Ott U., Herrmann S., and Agee C. B. 2014. Modern atmospheric signatures in 4.4 Ga Martian meteorite NWA 7034. *Earth and Planetary Science Letters* 400:77–87. https://doi.org/10.1016/J.EPSL.2014.05.008.

Cassata W. S., Shuster D. L., Renne P. R., and Weiss B. P. 2010. Evidence for shock heating and constraints on Martian surface temperatures revealed by 40Ar/39Ar thermochronometry of Martian meteorites. *Geochimica et Cosmochimica Acta* 74:6900–6920. https://doi.org/10.1016/J.GCA.2010.08.027.

Chamberlain T. E., Cole H. L., Dutton R. G., Greene G. C., and Tillman J. E. 1976. Atmospheric measurements on Mars: The Viking meteorology experiment. *Bulletin of the American Meteorological Society* 57:1094–1104. https://doi.org/10.1175/1520-0477(1976) 057 < 1094:AMOMTV > 2.0.CO;2.

Changela H. G. and Bridges J. C. 2010. Alteration assemblages in the nakhlites: Variation with depth on Mars. *Meteoritics & Planetary Science* 45:1847–1867. https://doi.org/10.1111/j.1945-5100.2010.01123.x.

Chastain B. K. and Kral T. A. 2010. Approaching Mars-like geochemical conditions in the laboratory: Omission of artificial buffers and reductants in a study of biogenic methane production on a smectite clay. *Astrobiology* 10:889–897. https://doi.org/10.1089/ast.2010.0480.

Christensen P. R., McSween H. Y., Bandfield J. L., Ruff S. W., Rogers A. D., Hamilton V. E., Gorelick N., Wyatt M. B., Jakosky B. M., Kieffer H. H., Malin M. C., and Moersch J. E. 2005. Evidence for magmatic evolution and diversity on Mars from infrared observations. *Nature* 436:504–509. https://doi.org/10.1038/nature03639.

Clark B. C. and Baird A. K. 1979. Is the Martian lithosphere sulfur rich? *Journal of Geophysical Research* 84:8395. https://doi.org/10.1029/JB084iB14p08395.

Clark B. C., Arvidson R. E., Gellert R., Morris R. V., Ming D. W., Richter L., Ruff S. W., Michalski J. R., Farrand W. H., Yen A., Herkenhoff K. E., Li R., Squyres S. W., Schröder C., Klingelhöfer G., and Bell J. F. 2007. Evidence for montmorillonite or its compositional equivalent in Columbia Hills, Mars. *Journal of Geophysical Research* 112:E06S01. https://doi.org/10.1029/2006je002756

Clark B. C., Morris R. V., Herkenhoff K. E., Farrand W. H., Gellert R., Jolliff B. L., Arvidson R. E., Squyres S. W., Mittelfehldt D. W., Ming D. W., and Yen A. S. 2016. Esperance: Multiple episodes of aqueous alteration involving fracture fills and coatings at Matijevic Hill, Mars. *American Mineralogist* 101:1515–1526. https://doi.org/10.2138/am-2016-5575.

Clayton R. N. 1993. Oxygen isotopes in meteorites. *Annual Review of Earth and Planetary Sciences* 21:115–149. https://doi.org/10.1146/annurev.ea.21.050193.000555.

Clifford S. M. 1993. A model for the hydrologic and climatic behavior of water on Mars. *Journal of Geophysical Research* 98:10,973. https://doi.org/10.1029/93JE00225.

Clifford S. M., Lasue J., Heggy E., Boisson J., McGovern P., and Max M. D. 2010. Depth of the Martian cryosphere: Revised estimates and implications for the existence and detection of subpermafrost groundwater. *Journal of Geophysical Research* 115:E07001. https://doi.org/10.1029/2009JE003462.

Cockell C. and Barlow N. G. 2002. Impact excavation and the search for subsurface life on Mars. *Icarus* 155:340–349. https://doi.org/10.1006/icar.2001.6725.

Cohen B. A., Swindle T. D., and Kring D. A. 2000. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. *Science* 290:1754–1756. https://doi.org/10.1126/SCIENCE.290.5497.1754.

Cohen B. E., Mark D. F., Cassata W. S., Lee M. R., Tomkinson T., and Smith C. L. 2017. Taking the pulse of Mars via dating of a plume-fed volcano. *Nature Communications* 8:640. https://doi.org/10.1038/s41467-017-00513-8.

Conrad P. G., Malespin C. A., Franz H. B., Pepin R. O., Trainer M. G., Schwenzer S. P., Atreya S. K., Freissinet C., Jones J. H., Manning H., Owen T., Pavlov A. A., Wiens R. C., Wong M. H., and Mahaffy P. R. 2016. In situ measurement of atmospheric krypton and xenon on Mars with Mars Science Laboratory. *Earth and Planetary Science Letters* 454:1–9. https://doi.org/10.1016/J.EPSL.2016.08.028.

Cooper B. L., McKay D. S., James J. T., Wallace W. T., and Lam C.-W. 2008. Physical and biological hazards of lunar dust and their impact on habitat and space suit design. In *2008 Joint Meeting of The Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of SEPM* (abstract #345-9).

COSPAR Planetary Protection Policy. 2011. COSPAR/IAU Workshop on Planetary Protection. https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf

Court R. W., Sims M. R., Cullen D. C., and Sephton M. A. 2014. Searching for life on Mars: Degradation of surfactant solutions used in organic extraction experiments. *Astrobiology* 14:733–752. https://doi.org/10.1089/ast.2013.1105.

Cousin A., Sautter V., Payré V., Forni O., Mangold N., Gasnault O., Le Deit L., Johnson J., Maurice S., Salvatore M., Wiens R. C., Gasda P., and Rapin W. 2017. Classification of igneous rocks analyzed by ChemCam at Gale crater, Mars. *Icarus* 288:265–283. https://doi.org/10.1016/J.ICARUS.2017.01.014.

Crawford I. 2012. The scientific legacy of Apollo. *Astronomy & Geophysics* 53:6.24–6.28. https://doi.org/10.1111/j.1468-4004.2012.53624.x

Cronin L. and Walker S. I. 2016. Beyond prebiotic chemistry: What dynamic network properties allow the emergence of life? *Science* 352:1174–1175. https://doi.org/10.1126/science.aaf6310.

Cuadros J., Cesarano M., Dubbin W., Smith S. W., Davey A., Spiro B., Burton R. G. O., and Jungblut A. D. 2018. Slow weathering of a sandstone-derived Podzol (Falkland Islands) resulting in high content of a non-crystalline silicate. *American Mineralogist* 103:109–124. https://doi.org/10.2138/am-2018-6230.

Cull S. C., Arvidson R. E., Catalano J. G., Ming D. W., Morris R. V., Mellon M. T., and Lemmon M. 2010. Concentrated perchlorate at the Mars Phoenix landing site: Evidence for thin film liquid water on Mars. *Geophysical Research Letters* 37. https://doi.org/10.1029/2010GL045269.

D'Hondt S., Inagaki F., Alvarez Zarikian C. A., and Expedition 329 Scientists. 2010. South Pacific gyre subseafloor life: Expedition 329 of the riserless drilling platform Papeete, Tahiti, to Auckland, New Zealand sites. In *Proceedings of the Integrated Ocean Drilling Program*, vol. 329, U1365–U1371. http://publications.iodp.org/proceedings/329/329title.htm.

D'Hondt S., Inagaki F., Zarikian C. A., Abrams L. J., Dubois N., Engelhardt T., Evans H., Ferdelman T., Gribsholt B., Harris R. N., Hoppie B. W., Hyun J.-H., Kallmeyer J., Kim J., Lynch J. E., McKinley C. C., Mitsunobu S., Morono Y., Murray R. W., Pockalny R., Sauvage J., Shimono T., Shiraishi F., Smith D. C., Smith-Duque C. E., Spivack A. J., Steinsbu B. O., Suzuki Y., Szpak M., Toffin L., Uramoto G., Yamaguchi Y. T., G-liang Zhang, Zhang X.-H., and Ziebis W. 2015. Presence of oxygen and aerobic communities from sea floor to basement in deep-sea sediments. *Nature Geoscience* 8:299–304. https://doi.org/10.1038/ngeo2387.

Dabney J., Meyer M., and Paabo S. 2013a. Ancient DNA damage. *Cold Spring Harbor Perspectives in Biology* 5: a012567. https://doi.org/10.1101/cshperspect.a012567.

Dabney J., Knapp M., Glocke I., Gansauge M.-T., Weihmann A., Nickel B., Valdiosera C., García N., Pääbo S., Arsuaga J. L., and Meyer M. 2013b. Complete mitochondrial genome sequence of a Middle Pleistocene cave bear reconstructed from ultrashort DNA fragments. *Proceedings of the National Academy of Sciences* 110:15,758–15,763. https://doi.org/10.1073/pnas.1314445110.

Darwin C. and Darwin F. S. 1887. *Darwin online: Life and letters and autobiography*. London: John Murray. http://darwin-online.org.uk/EditorialIntroductions/Freeman_LifeandLettersandAutobiography.html

Dauphas N. and Pourmand A. 2011. Hf–W–Th evidence for rapid growth of Mars and its status as a planetary embryo. *Nature* 473:489–492. https://doi.org/10.1038/nature10077.

Dauphin L. A., Moser B. D., and Bowen M. D. 2009. Evaluation of five commercial nucleic acid extraction kits for their ability to inactivate *Bacillus anthracis* spores and comparison of DNA yields from spores and spiked environmental samples. *Journal of Microbiological Methods* 76:30–37. https://doi.org/10.1016/J.MIMET.2008.09.004.

Davies J. H. F. L., Stern R. A., Heaman L. M., Moser D. E., Walton E. L., and Vennemann T. 2018. Evaluating baddeleyite oxygen isotope analysis by secondary ion mass spectrometry (SIMS). *Chemical Geology* 479:113–122. https://doi.org/10.1016/J.CHEMGEO.2018.01.002.

Debaille V., Brandon A. D., Yin Q. Z., and Jacobsen B. 2007. Coupled 142Nd-143Nd evidence for a protracted magma ocean in Mars. *Nature* 450:525–528. https://doi.org/10.1038/nature06317.

Debaille V., Brandon A. D., O'Neill C., Yin Q.-Z., and Jacobsen B. 2009. Early Martian mantle overturn inferred from isotopic composition of nakhlite meteorites. *Nature Geoscience* 2:548–552. https://doi.org/10.1038/ngeo579.

D'Elia T., Veerapaneni R., and Rogers S. O. 2008. Isolation of microbes from Lake Vostok accretion ice. *Applied and Environmental Microbiology* 74:4962–4965. https://doi.org/10.1128/AEM.02501-07.

Des Marais D. J. 2001. Isotopic evolution of the biogeochemical carbon cycle during the Precambrian. *Reviews in Mineralogy and Geochemistry* 43:555–578. https://doi.org/10.2138/gsrmg.43.1.555.

Des Marais D. J. 2004. Biogeochemical cycles of carbon and sulfur on early Earth (and on Mars?). In *Second Conference on Early Mars*.

Des Marais D. J. and Canfield D. E. 1994. The carbon isotope biogeochemistry of microbial mats. In *Microbial mats*. Berlin/Heidelberg: Springer. pp. 289–298. https://doi.org/10.1007/978-3-642-78991-5_30

Des Marais D. J. and Jahnke L. L. 2018. Biosignatures of cellular components and metabolic activity. In *Biosignatures for astrobiology*, edited by Westall F. and Cavalazzi B. Springer International Publishing.

Des Marais D. J., Nuth J. A., Allamandola L. J., Boss A. P., Farmer J. D., Hoehler T. M., Jakosky B. M., Meadows V. S., Pohorille A., Runnegar B., and Spormann A. M. 2008. The NASA astrobiology roadmap. *Astrobiology* 8:715–730. https://doi.org/10.1089/ast.2008.0819.

De Vera J.-P., Schulze-Makuch D., Khan A., Lorek A., Koncz A., and Möhlmann D. 2014. Adaptation of an Antarctic lichen to Martian niche conditions can occur within 34 days. *Planetary and Space Science* 98:182–190. https://doi.org/10.1016/J.PSS.2013.07.014.

Dickinson W. R. 1970. Interpreting detrital modes of graywacke and arkose. *Journal of Sedimentary Petrology* 40:695–707. https://doi.org/10.1306/74d72018-2b21-11d7-8648000102c1865d.

Dickson M. H. and Fanelli M. 2004. What is geothermal energy? International Geothermal Association, Bochum. http://geothermalcommunities.eu/assets/elearning/1.2.Geothermal_energy_enMeryDickson.pdf

Djokic T., Van Kranendonk M. J., Campbell K. A., Walter M. R., and Ward C. R. 2017. Earliest signs of life on land preserved in ca. 3.5 Ga hot spring deposits. *Nature Communications*, 8:15,263. https://doi.org/10.1038/ncomms15263

Dodd M. S., Papineau D., Grenne T., Slack J. F., Rittner M., Pirajno F., O'Neil J., and Little C. T. S. 2017. Evidence for early life in Earth's oldest hydrothermal vent precipitates. *Nature* 543:60–64. https://doi.org/10.1038/nature21377.

Dorn R. I. 2013. 4Rock coatings. In *Treatise on Geomorphology*. Amsterdam: Elsevier. pp. 70–97. https://doi.org/10.1016/b978-0-12-374739-6.00066-x

Dos Santos R., Patel M., Cuadros J., and Martins Z. 2016. Influence of mineralogy on the preservation of amino acids under simulated Mars conditions. *Icarus* 277:342–353. https://doi.org/10.1016/J.ICARUS.2016.05.029.

Drake B. G. 2009. Human Exploration of Mars Design Reference Architecture 5.0. NASA-SP-2009-566. https://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf

Drake B. D., Campbell K. A., Rowland J. V., Guido D. M., Browne P. R. L., and Rae A. 2014. Evolution of a dynamic paleo-hydrothermal system at Mangatete, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research* 282:19–35. https://doi.org/10.1016/J.JVOLGEORES.2014.06.010.

Dromart G., Quantin C., and Broucke O. 2007. Stratigraphic architectures spotted in southern Melas Chasma, Valles Marineris, Mars. *Geology* 35:363. https://doi.org/10.1130/G23350A.1.

Dundas C. M., McEwen A. S., Chojnacki M., Milazzo M. P., Byrne S., McElwaine J. N., and Urso A. 2017. Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water. *Nature Geoscience* 10:903–907. https://doi.org/10.1038/s41561-017-0012-5.

Dundas C. M., Bramson A. M., Ojha L., Wray J. J., Mellon M. T., Byrne S., McEwen A. S., Putzig N. E., Viola D., Sutton S., Clark E., and Holt J. W. 2018. Exposed subsurface ice sheets in the Martian mid-latitudes. *Science* 359:199–201. https://doi.org/10.1126/science.aao1619.

Duvet L., Beyer F., Delfa J., and Zekri E. 2018. ESA Sample fetch rover: Heritage and way forward. In *2nd International Mars Sample Return Conference* (abstract #6122).

Edgar L. A., Gupta S., Rubin D. M., Lewis K. W., Kocurek G. A., Anderson R. B., Bell J. F., Dromart G., Edgett K. S., Grotzinger J. P., Hardgrove C., Kah L. C., Leveille R., Malin M. C., Mangold N., Milliken R. E., Minitti M., Palucis M., Rice M., Rowland S. K., Schieber J., Stack K. M., Sumner D. Y., Wiens R. C., Williams R. M. E., and Williams A. J. 2018. Shaler: In situ analysis of a fluvial sedimentary deposit on Mars. *Sedimentology* 65:96–122. https://doi.org/10.1111/sed.12370.

Edgett K. S. 2016. The other sedimentary rocks of early Mars (abstract #1379). 47th Lunar and Planetary Science Conference. CD-ROM.

Edwards C. 2017. Mars sample return capability development: Mars ascent vehicle and mars on-orbit rendezvous. In *Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences*. http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_183720.pdf

Edwards C. S. and Ehlmann B. L. 2015. Carbon sequestration on Mars. *Geology* 43:863–866. https://doi.org/10.1130/G36983.1.

Edwards L. E. and Powars D. S. 2003. Impact damage to dinocysts from the late Eocene Chesapeake Bay event. *Palaios* 18:275–285. https://doi.org/10.1669/0883-1351(2003) 018 < 0275:IDTDFT > 2.0.CO;2.

Edwards P. H., Bridges J. C., Wiens R., Anderson R., Dyar D., Fisk M., Thompson L., Gasda P., Filiberto J., Schwenzer S. P., Blaney D., and Hutchinson I. 2017. Basalt-trachybasalt samples in Gale Crater, Mars. *Meteoritics & Planetary Science* 52:2931–2410. https://doi.org/10.1111/maps.12953.

Ehlmann B. L. and Edwards C. S. 2014. Mineralogy of the Martian surface. *Annual Review of Earth and Planetary Sciences* 42:291–315. https://doi.org/10.1146/annurev-earth-060313-055024.

Ehlmann B. L. and Mustard J. F. 2012. An in-situ record of major environmental transitions on early Mars at Northeast Syrtis Major. *Geophysical Research Letters* 39. https://doi.org/10.1029/2012GL051594.

Ehlmann B. L., Mustard J. F., Fassett C. I., Schon S. C., Head J. W. III, Des Marais D. J., Grant J. A., and Murchie S. L. 2008. Clay minerals in delta deposits and organic preservation potential on Mars. *Nature Geoscience* 1:355–358. https://doi.org/10.1038/ngeo207.

Ehlmann B. L., Mustard J. F., Swayze G. A., Clark R. N., Bishop J. L., Poulet F., Des Marais D. J., Roach L. H., Milliken R. E., Wray J. J., Barnouin-Jha O., and Murchie S. L. 2009. Identification of hydrated silicate minerals on Mars using MRO-CRISM: Geologic context near Nili Fossae and implications for aqueous alteration. *Journal of Geophysical Research* 114:E00D08. https://doi.org/10.1029/2009je003339

Ehlmann B. L., Mustard J. F., and Murchie S. L. 2010. Geologic setting of serpentine deposits on Mars. *Geophysical Research Letters* 37. https://doi.org/10.1029/2010GL042596.

Ehlmann B. L., Mustard J. F., Murchie S. L., Bibring J.-P., Meunier A., Fraeman A. A., and Langevin Y. 2011a. Subsurface water and clay mineral formation during the early history of Mars. *Nature* 479:53–60. https://doi.org/10.1038/nature10582.

Ehlmann B. L., Mustard J. F., Clark R. N., Swayze G. A., and Murchie S. L. 2011b. Evidence for low-grade metamorphism, hydrothermal alteration, and diagenesis on Mars from phyllosilicate mineral assemblages. *Clays and Clay Minerals* 59:359–377. https://doi.org/10.1346/CCMN.2011.0590402.

Ehlmann B. L., Anderson F. S., Andrews-Hanna J., Catling D. C., Christensen P. R., Cohen B. A., Cohen B. A., Dressing C. D., Edwards C. S., Elkins-Tanton L. T., Farley K. A., Fassett C. I., Fischer W. W., Fraeman A. A., Golombek M. P., Hamilton V. E., Hayes A. G., Herd C. D. K., Horgan B., Hu R., Jakosky B. M., Johnson J. R., Kasting J. F., Kerber L., Kinch K. M., Kite E. S., Knutson H. A., Lunine J. I., Mahaffy P. R., Mangold N., McCubbin F. M., Mustard J. F., Niles P. B., Quantin-Nataf C., Rice M. S., Stack K. M., Stevenson D. J., Stewart S. T., Toplis M. J., Usui T., Weiss B. P., Werner S. C., Wordsworth R. D., Wray J. J., Yingst R. A., Yung Y. L., and Zahnle K. J. 2016. The sustainability of habitability on terrestrial planets: Insights, questions, and needed measurements from Mars for understanding the evolution of Earth-like worlds. *Journal of Geophysical Research: Planets* 121:1927–1961. https://doi.org/10.1002/2016JE005134.

Ehlmann B. L., Edgett K. S., Sutter B., Achilles C. N., Litvak M. L., Lapotre M. G. A., Sullivan R., Fraeman A. A., Arvidson R. E., Blake D. F., Bridges N. T., Conrad P. G., Cousin A., Downs R. T., Gabriel T. S. J., Gellert R., Hamilton V. E., Hardgrove C., Johnson J. R., Kuhn S., Mahaffy P. R., Maurice S., McHenry M., Meslin P. Y., Ming D. W., Minitti M. E., Morookian J. M., Morris R. V., O'Connell-Cooper C. D., Pinet P. C., Rowland S. K., Schröder S., Siebach K. L., Stein N. T., Thompson L. M., Vaniman D. T., Vasavada A. R., Wellington D. F., Wiens R. C., and Yen A. S. 2017. Chemistry, mineralogy, and grain properties at Namib and High dunes, Bagnold dune field, Gale crater, Mars: A synthesis of Curiosity rover observations. *Journal of Geophysical Research: Planets* 122:2510–2543. https://doi.org/10.1002/2017JE005267.

Eigenbrode J. L., Summons R. E., Steele A., Freissinet C., Millan M., Navarro-González R., Sutter B., McAdam A. C., Franz H. B., Glavin D. P., Archer P. D., Mahaffy P. R., Conrad P. G., Hurowitz J. A., Grotzinger J. P., Gupta S., Ming D. W., Sumner D. Y., Szopa C., Malespin C., Buch A., and Coll P. 2018. Organic matter preserved in 3-billion-year-old mudstones at Gale crater, Mars. *Science* 360:1096–1101. https://doi.org/10.1126/science.aas9185.

Emerson J. B., Adams R. I., Román C. M. B., Brooks B., Coil D. A., Dahlhausen K., Ganz H. H., Hartmann E. M., Hsu T., Justice N. B., Paulino-Lima I. G., Luongo J. C., Lymperopoulou D. S., Gomez-Silvan C., Rothschild-Mancinelli B., Balk M., Huttenhower C., Nocker A., Vaishampayan P., and Rothschild L. J. 2017. Schrödinger's microbes: Tools for distinguishing the living from the dead in microbial ecosystems. *Microbiome* 5:86. https://doi.org/10.1186/s40168-017-0285-3.

Encrenaz T., Greathouse T. K., Lefèvre F., Montmessin F., Forget F., Fouchet T., DeWitt C., Richter M. J., Lacy J. H., Bézard B., and Atreya S. K. 2015. Seasonal variations of hydrogen peroxide and water vapor on Mars: Further indications of heterogeneous chemistry. *Astronomy & Astrophysics* 578:A127. https://doi.org/10.1051/0004-6361/201425448.

Engel M. H. and Macko S. A. 1993. *Organic geochemistry: Principles and applications*. New York: Plenum Press.

Englert P., Bishop J. L., Gibson E., and Koeberl C. 2013. Subsurface salts in Antarctic dry valley soils (abstract #1804). 44th Lunar and Planetary Science Conference. CD-ROM.

Epstein E. 1972. *Mineral nutrition of plants: Principles and perspectives*, vol. 56. New York: Wiley-Blackwell. https://doi.org/10.1002/sce.3730560420.

Ertem G., Ertem M. C., McKay C. P., and Hazen R. M. 2016. Shielding biomolecules from effects of radiation by Mars analogue minerals and soils. *International Journal of Astrobiology* 16:280–285. https://doi.org/10.1017/S1473550416000331.

Etiope G. 2017. Methane origin in the Samail ophiolite: Comment on "Modern water/rock reactions in Oman hyperalkaline peridotite aquifers and implications for microbial habitability" [Geochim. Cosmochim. Acta 179 (2016) 217–241]. *Geochimica et Cosmochimica Acta* 197:467–470. https://doi.org/10.1016/J.GCA.2016.08.001.

Etiope G. 2018. Understanding the origin of methane on Mars through isotopic and molecular data from NOMAD (ExoMars): Will there be more answers or questions? In *Scientific Workshop: "From Mars Express to ExoMars."* Madrid, Spain: ESAC.

Evans D. A. D. 2003. True polar wander and supercontinents. *Tectonophysics* 362:303–320. https://doi.org/10.1016/S0040-1951(02)000642-X.

Fairén A. G., Davila A. F., Gago-Duport L., Haqq-Misra J. D., Gil C., McKay C. P., and Kasting J. F. 2011. Cold glacial oceans would have inhibited phyllosilicate sedimentation on early Mars. *Nature Geoscience* 4:667–670. https://doi.org/10.1038/ngeo1243.

Farley K. A., Malespin C., Mahaffy P., Grotzinger J. P., Vasconcelos P. M., Milliken R. E., Malin M., Edgett K. S., Pavlov A. A., Hurowitz J. A., Grant J. A., Miller H. B., Arvidson R., Beegle L., Calef F., Conrad P. G., Dietrich W. E., Eigenbrode J., Gellert R., Gupta S., Hamilton V., Hassler D. M., Lewis K. W., McLennan S. M., Ming D., Navarro-González R., Schwenzer S. P., Steele A., Stolper E. M., Sumner D. Y., Vaniman D., Vasavada A., Williford K., Wimmer-Schweingruber R. F., and MSL Science Team. 2014. In situ radiometric and exposure age dating of the Martian surface. *Science* 343:1247166. https://doi.org/10.1126/science.1247166.

Farley K. A., Martin P., Archer P. D., Atreya S. K., Conrad P. G., Eigenbrode J. L., Fairén A. G., Franz H. B., Freissinet C., Glavin D. P., Mahaffy P. R., Malespin C., Ming D. W., Navarro-Gonzalez R., and Sutter B. 2016. Light and variable $^{37}Cl/^{35}Cl$ ratios in rocks from Gale

Crater, Mars: Possible signature of perchlorate. *Earth and Planetary Science Letters* 438:14–24. https://doi.org/10.1016/J.EPSL.2015.12.013.

Farmer J. D. 1999. Taphonomic modes in microbial fossilization. In *Size Limits of Very Small Microorganisms: Proceedings of a Workshop, Space Studies Board, National Research Council, National Academies Press, Washington, DC*. Washington, D.C.: National Academies Press. pp. 94–102. https://doi.org/10.17226/9638

Farmer J. D. 2000. Hydrothermal systems: Doorways to early biosphere evolution. *GSA Today*, 10:1–4. https://ci.nii.ac.jp/naid/10017464962/

Farmer J. D. and Des Marais D. J. 1999. Exploring for a record of ancient Martian life. *Journal of Geophysical Research: Planets* 104:26,977–26,995. https://doi.org/10.1029/1998JE000540.

Farquhar J., Thiemens M. H., and Jackson T. 1998. Atmosphere-surface interactions on Mars: Delta 17O measurements of carbonate from ALH 84001. *Science* 280:1580–1582. https://doi.org/10.1126/SCIENCE.280.5369.1580.

Farquhar J., Savarino J., Airieau S., and Thiemens M. H. 2001. Observation of wavelength-sensitive mass-independent sulfur isotope effects during SO_2 photolysis: Implications for the early atmosphere. *Journal of Geophysical Research: Planets* 106:32,829–32,839. https://doi.org/10.1029/2000JE001437.

Farrand W. H., Glotch T. D., and Horgan B. 2014. Detection of copiapite in the northern Mawrth Vallis region of Mars: Evidence of acid sulfate alteration. *Icarus* 241:346–357. https://doi.org/10.1016/J.ICARUS.2014.07.003.

Farrand W. H., Johnson J. R., Rice M. S., Wang A., and Bell J. F. 2016. VNIR multispectral observations of aqueous alteration materials by the Pancams on the Spirit and Opportunity Mars Exploration Rovers. *American Mineralogist* 101:2005–2019. https://doi.org/10.2138/am-2016-5627.

Fassett C. I. and Head J. W. 2005. Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region. *Geophysical Research Letters* 32. https://doi.org/10.1029/2005GL023456.

Fassett C. I. and Head J. W. 2008. Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology. *Icarus* 198:37–56. https://doi.org/10.1016/J.ICARUS.2008.06.016.

Faucher B., Lacelle D., Davila A., Pollard W., Fisher D., and McKay C. P. 2017. Physicochemical and biological controls on carbon and nitrogen in Permafrost from an ultraxerous environment, McMurdo dry valleys of Antarctica. *Journal of Geophysical Research: Biogeosciences* 122:2593–2604. https://doi.org/10.1002/2017JG004006.

Filiberto J. 2017. Geochemistry of Martian basalts with constraints on magma genesis. *Chemical Geology* 466:1–14. https://doi.org/10.1016/J.CHEMGEO.2017.06.009.

Filiberto J. and Schwenzer S. P., ed. 2018. *Volatiles in the Martian crust*. Amsterdam, Netherlands: Elsevier Science Ltd.

Filiberto J. and Treiman A. H. 2009. Martian magmas contained abundant chlorine, but little water. *Geology* 37:1087–1090. https://doi.org/10.1130/G30488A.1.

Filiberto J., Musselwhite D. S., Gross J., Burgess K., Le L., and Treiman A. H. 2010a. Experimental petrology, crystallization history, and parental magma characteristics of olivine-phyric shergottite NWA 1068: Implications for the petrogenesis of "enriched" olivine-phyric shergottites. *Meteoritics & Planetary Science* 45:1258–1270. https://doi.org/10.1111/j.1945-5100.2010.01080.x.

Filiberto J., Dasgupta R., Kiefer W. S., and Treiman A. H. 2010b. High pressure, near-liquidus phase equilibria of the Home Plate basalt Fastball and melting in the Martian mantle. *Geophysical Research Letters* 37. https://doi.org/10.1029/2010gl043999

Filiberto J., Baratoux D., Beaty D., Breuer D., Farcy B. J., Grott M., Jones J. H., Kiefer W. S., Mane P., McCubbin F. M., and Schwenzer S. P. 2016a. A review of volatiles in the Martian interior. *Meteoritics & Planetary Science* 51:1935–1958. https://doi.org/10.1111/maps.12680.

Filiberto J., Gross J., and McCubbin F. M. 2016b. Constraints on the water, chlorine, and fluorine content of the Martian mantle. *Meteoritics & Planetary Science* 51:2023–2035. https://doi.org/10.1111/maps.12624.

Filiberto J., McCubbin F., and Taylor G. J. 2018. Volatiles in Martian magmas and the interior: Inputs of volatiles into the crust and atmosphere. In *Volatiles in the Martian crust*, edited by Filiberto J. and Schwenzer S. P. Amsterdam, Netherlands: Elsevier Science Ltd. pp. 13–33.

Fisk M., Popa R., Bridges N. T., Rennó N., Mischna M., Moores J., and Wiens R. C. 2013. Habitability of transgressing mars Dunes (abstract #1719). 44th Lunar and Planetary Science Conference. CD-ROM.

Folkner W. M., Yoder C. F., Yuan D. N., Standish E. M., and Preston R. A. 1997. Interior structure and seasonal mass redistribution of Mars from radio tracking of Mars Pathfinder. *Science* 278:1749–1752. https://doi.org/10.1126/science.278.5344.1749

Fornaro T., Brucato J. R., Pace E., Guidi M. C., Branciamore S., and Pucci A. 2013. Infrared spectral investigations of UV irradiated nucleobases adsorbed on mineral surfaces. *Icarus* 226:1068–1085. https://doi.org/10.1016/J.ICARUS.2013.07.024.

Foucher F., Westall F., Brandstätter F., Demets R., Parnell J., Cockell C. S., Edwards H. G. M., Bény J. M., and Brack A. 2010. Testing the survival of microfossils in artificial Martian sedimentary meteorites during entry into Earth's atmosphere: The STONE 6 experiment. *Icarus* 207:616–630. https://doi.org/10.1016/j.icarus.2009.12.014.

Franz H. B., Trainer M. G., Wong M. H., Mahaffy P. R., Atreya S. K., Manning H. L. K., and Stern J. C. 2015. Reevaluated Martian atmospheric mixing ratios from the mass spectrometer on the Curiosity rover. *Planetary and Space Science* 109–110:154–158. https://doi.org/10.1016/J.PSS.2015.02.014.

Franz H. B., McAdam A. C., Ming D. W., Freissinet C., Mahaffy P. R., Eldridge D. L., Fischer W. W., Grotzinger J. P., House C. H., Hurowitz J. A., McLennan S. M., Schwenzer S. P., Vaniman D. T., Archer P. D. Jr, Atreya S. K., Conrad P. G., Dottin J. W. III, Eigenbrode J. L., Farley K. A., Glavin D. P., Johnson S. S., Knudson C. A., Morris R. V., Navarro-González R., Pavlov A. A., Plummer R., Rampe E. B., Stern J. C., Steele A., Summons R. E., and Sutter B. 2017. Large sulfur isotope fractionations in Martian sediments at Gale crater. *Nature Geoscience* 10:658–662. https://doi.org/10.1038/ngeo3002.

Freissinet C., Glavin D. P., Mahaffy P. R., Miller K. E., Eigenbrode J. L., Summons R. E., Brunner A. E., Buch A., Szopa C., Archer P. D. Jr., Franz H. B., Atreya S. K., Brinckerhoff W. B., Cabane M., Coll P., Conrad P. G., Des Marais D. J., Dworkin J. P., Fairén A. G., François P., Grotzinger J. P., Kashyap S., Ten Kate I. L., Leshin L. A., Malespin C. A., Martin M. G., Martin-Torres F. J., McAdam A. C., Ming D. W., Navarro-González R., Pavlov A. A., Prats B. D., Squyres S. W., Steele A., Stern J. C., Sumner D. Y., Sutter B., Zorzano M.-P., and the MSL Science Team. 2015. Organic molecules in the Sheepbed Mudstone, Gale Crater, Mars. *Journal of Geophysical Research: Planets* 120:495–514. https://doi.org/10.1002/2014JE004737.

Frey M. and Robinson D. 1998. *Low-grade metamorphism*. Hoboken, New Jersey: Blackwell Science.

Friedmann E. I. 1993. *Antarctic microbiology*. Hoboken, New Jersey: Wiley-Liss.

Frydenvang J., Gasda P. J., Hurowitz J. A., Grotzinger J. P., Wiens R. C., Newsom H. E., Edgett K. S., Watkins J., Bridges J. C., Maurice S., Fisk M. R., Johnson J. R., Rapin W., Stein N. T., Clegg S. M., Schwenzer S. P., Bedford C. C., Edwards P., Mangold N., Cousin A., Anderson R. B., Payré V., Vaniman D., Blake D. F., Lanza N. L., Gupta S., Van Beek J., Sautter V., Meslin P.-Y., Rice M., Milliken R., Gellert R., Thompson L., Clark B. C., Sumner D. Y., Fraeman A. A., Kinch K. M., Madsen M. B., Mitrofanov I. G., Jun I., Calef F., and Vasavada A. R. 2017. Diagenetic silica enrichment and late-stage groundwater activity in Gale crater, Mars. *Geophysical Research Letters* 44:4716–4724. https://doi.org/10.1002/2017GL073323.

Gaier J. 2005. The effects of lunar dust on EVA systems during the apollo missions. NASA/TM—213610. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050160460.pdf

Gainey S. R., Hausrath E. M., Adcock C. T., Tschauner O., Hurowitz J. A., Ehlmann B. L., Xiao Y., and Bartlett C. L. 2017. Clay mineral formation under oxidized conditions and implications for paleoenvironments and organic preservation on Mars. *Nature Communications* 8:1230. https://doi.org/10.1038/s41467-017-01235-7.

Garzanti E. 2016. From static to dynamic provenance analysis—Sedimentary petrology upgraded. *Sedimentary Geology* 336:3–13. https://doi.org/10.1016/J.SEDGEO.2015.07.010.

Gay A. L. and Grandstaff D. E. 1980. Chemistry and mineralogy of Precambrian paleosols at Elliot Lake, Ontario, Canada. *Precambrian Research* 12:349–373. https://doi.org/10.1016/0301-9268(80)90035-2.

Genereux D. P., Webb M., and Solomon D. K. 2009. Chemical and isotopic signature of old groundwater and magmatic solutes in a Costa Rican rain forest: Evidence from carbon, helium, and chlorine. *Water Resources Research* 45. https://doi.org/10.1029/2008wr007630

Georgiou C. D. and Deamer D. W. 2014. Lipids as universal biomarkers of extraterrestrial life. *Astrobiology* 14:541–549. https://doi.org/10.1089/ast.2013.1134.

Ghiorse W. C. and Wilson J. T. 1988. Microbial ecology of the terrestrial subsurface. *Advances in Applied Microbiology* 33:107–172. https://doi.org/10.1016/S0065-2164(08)70206-5.

Giardini A. A. and Salotti C. A. 1969. Kinetics and relations in the calcite-hydrogen reaction and reactions in the dolomite-hydrogen and siderite-hydrogen systems. *American Mineralogist* 54:1151–1172. http://www.htracyhall.org/ocr/HTH-Archives/Cabinet 2/G/Giardini, A.A/Giardini, A.A.-7538_OCR.pdf

Gibson E. K., Wentworth S. J., and McKay D. S. 1983. Chemical weathering and diagenesis of a cold desert soil from Wright Valley, Antarctica: An analog of Martian weathering processes. *Journal of Geophysical Research* 88: A912. https://doi.org/10.1029/JB088iS02p0A912.

Gilmour J. D., Whitby J. A., and Turner G. 1999. Martian atmospheric xenon contents of Nakhla mineral separates: implications for the origin of elemental mass fractionation. *Earth and Planetary Science Letters* 166:139–147. https://doi.org/10.1016/S0012-821X(98)00283-0.

Gilmour J. D., Whitby J. A., and Turner G. 2000. Extraterrestrial xenon components in Nakhla (abstract #1513). 31st Lunar and Planetary Science Conference. CD-ROM.

Gislason S. R., Oelkers E. H., Eiriksdottir E. S., Kardjilov M. I., Gisladottir G., Sigfusson B., Snorrason A., Elefsen S., Hardardottir J., Torssander P., and Oskarsson N. 2009. Direct evidence of the feedback between climate and weathering. *Earth and Planetary Science Letters* 277:213–222. https://doi.org/10.1016/J.EPSL.2008.10.018.

Gogarten-Boekels M., Hilario E., and Gogarten J. P. 1995. The effects of heavy meteorite bombardment on the early evolution—The emergence of the three domains of life. *Origins of Life and Evolution of the Biosphere* 25:251–264. https://doi.org/10.1007/BF01581588.

Gold T. 1992. The deep, hot biosphere. *Proceedings of the National Academy of Sciences* 89:6045–6049.

Goldenfeld N., Biancalani T., and Jafarpour F. 2017. Universal biology and the statistical mechanics of early life. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 375:20160341. https://doi.org/10.1098/rsta.2016.0341

Gomes R., Levison H. F., Tsiganis K., and Morbidelli A. 2005. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. *Nature* 435:466–469. https://doi.org/10.1038/nature03676.

Goordial J., Davila A., Lacelle D., Pollard W., Marinova M. M., Greer C. W., DiRuggiero J., McKay C. P., and Whyte L. G. 2016. Nearing the cold-arid limits of microbial life in permafrost of an upper dry valley, Antarctica. *The ISME Journal* 10:1613–1624. https://doi.org/10.1038/ismej.2015.239.

Goossens S., Sabaka T. J., Genova A., Mazarico E., Nicholas J. B., and Neumann G. A. 2017. Evidence for a low bulk crustal density for Mars from gravity and topography. *Geophysical Research Letters* 44:7686–7694. https://doi.org/10.1002/2017GL074172.

Goudge T. A., Head J. W., Mustard J. F., and Fassett C. I. 2012. An analysis of open-basin lake deposits on Mars: Evidence for the nature of associated lacustrine deposits and post-lacustrine modification processes. *Icarus* 219:211–229. https://doi.org/10.1016/J.ICARUS.2012.02.027.

Goudge T. A., Mustard J. F., Head J. W., Fassett C. I., and Wiseman S. M. 2015. Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars. *Journal of Geophysical Research: Planets* 120:775–808. https://doi.org/10.1002/2014JE004782.

Goudge T. A., Milliken R. E., Head J. W., Mustard J. F., and Fassett C. I. 2017. Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration. *Earth and Planetary Science Letters* 458:357–365. https://doi.org/10.1016/J.EPSL.2016.10.056.

Goudge T. A., Mohrig D., Cardenas B. T., Hughes C. M., and Fassett C. I. 2018. Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars. *Icarus* 301:58–75. https://doi.org/10.1016/J.ICARUS.2017.09.034.

Grady M. M. and Wright I. 2006. The carbon cycle on early Earth–and on Mars? *Philosophical Transactions of the Royal Society B: Biological Sciences* 361:1703–1713. https://doi.org/10.1098/rstb.2006.1898.

Grady M. M., Wright I., Engrand C., and Siljeström S. 2018. The Rosetta Mission and the chemistry of organic species in Comet 67P/Churyumov-Gerasimenko. *Elements* 14:95–100. http://elementsmagazine.org/2018/04/16/rosetta-mission-organic-species-comet-67p/

Graur D. and Pupko T. 2001. The Permian bacterium that isn't. *Molecular Biology and Evolution* 18:1143–1146. https://doi.org/10.1093/oxfordjournals.molbev.a003887.

Greeley R., Kraft M., Sullivan R., Wilson G., Bridges N., Herkenhoff K., Kuzmin R. O., Malin M., and Ward W. 1999. Aeolian features and processes at the Mars Pathfinder landing site. *Journal of Geophysical Research: Planets* 104:8573–8584. https://doi.org/10.1029/98JE02553.

Grimm R. E., Harrison K. P., Stillman D. E., and Kirchoff M. R. 2017. On the secular retention of ground water and ice on Mars. *Journal of Geophysical Research: Planets* 122:94–109. https://doi.org/10.1002/2016JE005132.

Gross J., Filiberto J., and Bell A. S. 2013. Water in the Martian interior: Evidence for terrestrial MORB mantle-like volatile contents from hydroxyl-rich apatite in olivine–phyric shergottite NWA 6234. *Earth and Planetary Science Letters* 369–370:120–128. https://doi.org/10.1016/J.EPSL.2013.03.016.

Grott M., Morschhauser A., Breuer D., and Hauber E. 2011. Volcanic outgassing of CO_2 and H_2O on Mars. *Earth and Planetary Science Letters* 308:391–400. https://doi.org/10.1016/J.EPSL.2011.06.014.

Grott M., Baratoux D., Hauber E., Sautter V., Mustard J., Gasnault O., Ruff S. W., Karato S.-I., Debaille V., Knapmeyer M., Sohl F., Van Hoolst T., Breuer D., Morschhauser A., and Toplis M. J. 2013. Long-term evolution of the Martian crust-mantle system. *Space Science Reviews* 174:49–111. https://doi.org/10.1007/s11214-012-9948-3.

Grotzinger J. P. and and Milliken R. E. 2012. The sedimentary rock record of Mars: Distribution, origins, and global stratigraphy. In *Sedimentary geology of Mars*. SEPM (Society for Sedimentary Geology). pp. 1–48. https://doi.org/10.2110/pec.12.102.0001

Grotzinger J. P., Arvidson R. E., Bell J. F., Calvin W., Clark B. C., Fike D. A., Golombek M., Greeley R., Haldemann A., Herkenhoff K. E., Jolliff B. L., Knoll A. H., Malin M., McLennan S. M., Parker T., Soderblom L., Sohl-Dickstein J. N., Squyres S. W., and Watters W. A. 2005. Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns formation, Meridiani Planum. *Mars. Earth and Planetary Science Letters* 240:11–72. https://doi.org/10.1016/J.EPSL.2005.09.039.

Grotzinger J., Beaty D., Dromart G., Gupta S., Harris M., Hurowitz J., Kocurek G., McLennan S., Milliken R., Ori G. G., and Sumner D. 2011. Mars sedimentary geology: Key concepts and outstanding questions. *Astrobiology* 11:77–87. https://doi.org/10.1089/ast.2010.0571.

Grotzinger J. P., Hayes A. G., Lamb M. P., and McLennan S. M. 2013. Sedimentary processes on Earth, Mars, Titan, and Venus. In *Comparative climatology of terrestrial planets*, edited by Mackwell S. J. Tucson, Arizona: The University of Arizona Press. pp. 439–472. https://www.jstor.org/stable/j.ctt183gz90

Grotzinger J. P., Sumner D. Y., Kah L. C., Stack K., Gupta S., Edgar L., Rubin D., Lewis K., Schieber J., Mangold N., Milliken R., Conrad P. G., Des Marais D., Farmer J., Siebach K., Calef F. 3rd, Hurowitz J., McLennan S. M., Ming D., Vaniman D., Crisp J., Vasavada A., Edgett K. S., Malin M., Blake D., Gellert R., Mahaffy P., Wiens R. C., Maurice S., Grant J. A., Wilson S., Anderson R. C., Beegle L., Arvidson R., Hallet B., Sletten R. S., Rice M., Bell J. 3rd, Griffes J., Ehlmann B., Anderson R. B., Bristow T. F., Dietrich W. E., Dromart G., Eigenbrode J., Fraeman A., Hardgrove C., Herkenhoff K., Jandura L., Kocurek G., Lee S., Leshin L. A., Leveille R., Limonadi D., Maki J., McCloskey S., Meyer M., Minitti M., Newsom H., Oehler D., Okon A., Palucis M., Parker T., Rowland S., Schmidt M., Squyres S., Steele A., Stolper E., Summons R., Treiman A., Williams R., Yingst A., and MSL Science Team. 2014. A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale crater, Mars. *Science* 343:1242777. https://doi.org/10.1126/science.1242777.

Grotzinger J. P., Gupta S., Malin M. C., Rubin D. M., Schieber J., Siebach K., Sumner D. Y., Stack K. M., Vasavada A. R., Arvidson R. E., Calef F. 3rd, Edgar L., Fischer W. F., Grant J. A., Griffes J., Kah L. C., Lamb M. P., Lewis K. W., Mangold N., Minitti M. E., Palucis M., Rice M., Williams R. M., Yingst R. A., Blake D., Blaney D., Conrad P., Crisp J., Dietrich W. E., Dromart G., Edgett K. S., Ewing R. C., Gellert R., Hurowitz J. A., Kocurek G., Mahaffy P., McBride M. J., McLennan S. M., Mischna M., Ming D., Milliken R., Newsom H., Oehler D., Parker T. J., Vaniman D., Wiens R. C., and Wilson S. A. 2015. Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. *Science* 350:aac7575. https://doi.org/10.1126/science.aac7575

Guido D. M. and Campbell K. A. 2009. Jurassic hot-spring activity in a fluvial setting at La Marciana, Patagonia, Argentina. *Geological Magazine* 146:617–622. https://doi.org/10.1017/S0016756809006426.

Guido D. M. and Campbell K. A. 2011. Jurassic hot spring deposits of the Deseado Massif (Patagonia, Argentina): Characteristics and controls on regional distribution. *Journal of Volcanology and Geothermal Research* 203:35–47. https://doi.org/10.1016/J.JVOLGEORES.2011.04.001.

Guido D. M. and Campbell K. A. 2014. A large and complete Jurassic geothermal field at Claudia, Deseado Massif, Santa Cruz, Argentina. *Journal of Volcanology and Geothermal Research* 275:61–70. https://doi.org/10.1016/J.JVOLGEORES.2014.02.013.

Guido D. M. and Campbell K. A. 2017. Upper Jurassic travertine at El Macanudo, Argentine Patagonia: A fossil geothermal field modified by hydrothermal silicification and acid overprinting. *Geological Magazine* 155:1394–1412. https://doi.org/10.1017/S0016756817000498.

Gulick V. C. 1998. Magmatic intrusions and a hydrothermal origin for fluvial valleys on Mars. *Journal of Geophysical Research: Planets* 103:19,365–19,387. https://doi.org/10.1029/98JE01321.

Gutzmer J. and Beukes N. J. 1998. Earliest laterites and possible evidence for terrestrial vegetation in the Early Proterozoic. *Geology* 26:263. https://doi.org/10.1130/0091-7613(1998) 026 < 0263:ELAPEF > 2.3.CO;2.

Haberle R. M., Clancy R. T., Forget F., Smith M. D., and Zurek R. W. (Eds.). 2017. *The atmosphere and climate of*

Mars. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/9781139060172

Halevy I. and Head J. W. III. 2014. Episodic warming of early Mars by punctuated volcanism. *Nature Geoscience* 7:865–868. https://doi.org/10.1038/ngeo2293.

Halevy I., Fischer W. W., and Eiler J. M. 2011. Carbonates in the Martian meteorite Allan Hills 84001 formed at 18 ± 4 degrees C in a near-surface aqueous environment. *Proceedings of the National Academy of Sciences* 108:16,895–16,899. https://doi.org/10.1073/pnas.1109444108.

Haltigin T. and Smith C. L. 2014. International Mars Architecture for the Return of Samples (iMARS) Phase II Science Subteam Report—Science Management of Returned Samples. In *American Geophysical Union, Fall Meeting 2014* (abstract #P21D-3951).

Haltigin T., Lange C., Mugnuolo R., Smith C., Amundsen H., Bousquet P., Conley C., Debus A., Dias J., Falkner P., Gass V., Harri A.-M., Hauber E., Ivanov A. B., Ivanov A. O., Kminek G., Korablev O., Koschny D., Larranaga J., Marty B., McLennan S., Meyer M., Nilsen E., Orleanski P., Orosei R., Rebuffat D., Safa F., Schmitz N., Siljeström S., Thomas N., Vago J., Vandaele A.-C., Voirin T., and Whetsel C. 2018. iMARS Phase 2: A Draft Mission architecture and science management plan for the return of samples from Mars. *Astrobiology* 18:S-1–S-131. https://doi.org/10.1089/ast.2018.29027.mars

Hammes F., Berney M., and Egli T. 2010. Cultivation-independent assessment of bacterial viability. In *Advances in biochemical engineering/biotechnology*, vol. 124. pp. 123–150. https://doi.org/10.1007/10_2010_95

Handley K. M., Campbell K. A., Mountain B. W., and Browne P. R. L. 2005. Abiotic-biotic controls on the origin and development of spicular sinter: In situ growth experiments, Champagne Pool, Waiotapu, New Zealand. *Geobiology* 3:93–114. https://doi.org/10.1111/j.1472-4669.2005.00046.x.

Handley K. M., Turner S. J., Campbell K. A., and Mountain B. W. 2008. Silicifying biofilm exopolymers on a hot-spring microstromatolite: Templating nanometer-thick laminae. *Astrobiology* 8:747–770. https://doi.org/10.1089/ast.2007.0172.

Hansman R. J., Albert R., Gerdes A., and Ring U. 2018. Absolute ages of multiple generations of brittle structures by U-Pb dating of calcite. *Geology* 46:207–210. https://doi.org/10.1130/G39822.1.

Harper C. L., Nyquist L. E., Bansal B., Wiesmann H., and Shih C. Y. 1995. Rapid accretion and early differentiation of Mars indicated by ^{142}Nd/^{144}Nd in SNC meteorites. *Science* 267:213–217. https://doi.org/10.1126/SCIENCE.7809625.

Harrington A. D., Hylton S., and Schoonen M. A. A. 2012. Pyrite-driven reactive oxygen species formation in simulated lung fluid: Implications for coal workers' pneumoconiosis. *Environmental Geochemistry and Health* 34:527–538. https://doi.org/10.1007/s10653-011-9438-7.

Harrington A. D., McCubbin F. M., Kaur J., Smirnov A., Galdanes K., Schoonen M. A. A., Chen L. C., Tsirka S. E., and Gordon T. 2017. Acute meteorite dust exposure and pulmonary inflammation—Implications for human space exploration. In *Dust in the atmosphere of Mars* (abstract #6024).

Hartmann W. K. 2005. Martian cratering 8: Isochron refinement and the chronology of Mars. *Icarus* 174:294–320. https://doi.org/10.1016/J.ICARUS.2004.11.023.

Hartmann W. K. and Neukum G. 2001. Cratering chronology and the evolution of Mars. *Space Science Reviews* 96:165–194. https://doi.org/10.1023/A:1011945222010.

Haskin L. A., Wang A., Jolliff B. L., McSween H. Y., Clark B. C., Des Marais D. J., McLennan S. M., Tosca N. J., Hurowitz J. A., Farmer J. D., Yen A., Squyres S. W., Arvidson R. E., Klingelhöfer G., Schröder C., De Souza P. A. Jr., Ming D. W., Gellert R., Zipfel J., Brückner J., Bell J. F. III, Herkenhoff K., Christensen P. R., Ruff S., Blaney D., Gorevan S., Cabrol N. A., Crumpler L., Grant J., and Soderblom L. 2005. Water alteration of rocks and soils on Mars at the Spirit rover site in Gusev crater. *Nature* 436:66–69. https://doi.org/10.1038/nature03640.

Hausrath E. M., Treiman A. H., Vicenzi E., Bish D. L., Blake D., Sarrazin D., Hoehlerl P., Midtkandal I., Steele A., and Brantley S. L. 2008a. Short- and long-term olivine weathering in Svalbard: Implications for Mars. *Astrobiology* 8:1079–1092. https://doi.org/10.1089/ast.2007.0195.

Hausrath E. M., Navarre-Sitchler A. K., Sak P. B., Steefel C. I., and Brantley S. L. 2008b. Basalt weathering rates on Earth and the duration of liquid water on the plains of Gusev Crater, Mars. *Geology* 36:67. https://doi.org/10.1130/G24238A.1.

Hausrath E. M., Navarre-Sitchler A. K., Sak P. B., Williams J. Z., and Brantley S. L. 2011. Soil profiles as indicators of mineral weathering rates and organic interactions for a Pennsylvania diabase. *Chemical Geology* 290:89–100. https://doi.org/10.1016/J.CHEMGEO.2011.08.014.

Hausrath E. M., Ming D. W., Peretyazhko T. S., and Rampe E. B. 2018. Reactive transport and mass balance modeling of the Stimson sedimentary formation and altered fracture zones constrain diagenetic conditions at Gale crater, Mars. *Earth and Planetary Science Letters* 491:1–10. https://doi.org/10.1016/J.EPSL.2018.02.037.

Hayes J. M. 1993. Factors controlling 13C contents of sedimentary organic compounds: Principles and evidence. *Marine Geology* 113:111–125. https://doi.org/10.1016/0025-3227(93)90153-M.

Hayes J. M. 2001. Fractionation of carbon and hydrogen isotopes in biosynthetic processes. *Reviews in Mineralogy and Geochemistry* 43:225–277. https://doi.org/10.2138/gsrmg.43.1.225.

Hays L. E., Graham H. V., Des Marais D. J., Hausrath E. M., Horgan B., McCollom T. M., Parenteau M. N., Potter-McIntyre S. L., Williams A. J., and Lynch K. L. 2017. Biosignature preservation and detection in Mars analog environments. *Astrobiology* 17:363–400. https://doi.org/10.1089/ast.2016.1627.

Hazen R. M., Papineau D., Bleeker W., Downs R. T., Ferry J. M., McCoy T. J., Sverjensky D. A., and Yang H. 2008. Mineral evolution. *American Mineralogist* 93:1693–1720. https://doi.org/10.2138/am.2008.2955.

Head J. N., Melosh H. J., and Ivanov B. A. 2002. Martian meteorite launch: High-speed ejecta from small craters. *Science* 298:1752–1756. https://doi.org/10.1126/science.1077483.

Head J. W. 2012. Mars climate history: A geological perspective (abstract #2582). 43rd Lunar and Planetary Science Conference. CD-ROM.

Hecht M. H., McClean J. B., Pike W. T., Smith P. H., Madsen M. B., Rapp D., and Moxie Team. 2017. MOXIE, ISRU, and the history of in situ studies of the hazards of dust in human exploration of Mars (abstract

#1966). In *Dust in the atmosphere of Mars and its impact on human exploration* . Lunar and Planetary Institute.

Hendy C. H. 2000. The role of polar lake ice as a filter for glacial lacustrine sediments. *Geografiska Annaler: Series A, Physical Geography* 82:271–274. https://doi.org/10.1111/j.0435-3676.2000.00125.x.

Herd C. D. K. 2003. The oxygen fugacity of olivine-phyric Martian basalts and the components within the mantle and crust of Mars. *Meteoritics & Planetary Science* 38:1793–1805. https://doi.org/10.1111/j.1945-5100.2003.tb00015.x.

Herd C. D. K., Borg L. E., Jones J. H., and Papike J. J. 2002. Oxygen fugacity and geochemical variations in the Martian basalts: Implications for Martian basalt petrogenesis and the oxidation state of the upper mantle of Mars. *Geochimica et Cosmochimica Acta* 66:2025–2036. https://doi.org/10.1016/S0016-7037(02)00828-1.

Herd C. D. K., Walton E. L., Agee C. B., Muttik N., Ziegler K., Shearer C. K., Bell A. S., Santos A. R., Burger P. V., Simon J. I., Tappa M. J., McCubbin F. M., Gattacceca J., Lagroix F., Sanborn M. E., Yin Q.-Z., Cassata W. S., Borg L. E., Lindvall R. E., Kruijer T. S., Brennecka G. A., Kleine T., Nishiizumi K., and Caffee M. W. 2017. The Northwest Africa 8159 Martian meteorite: Expanding the Martian sample suite to the early Amazonian. *Geochimica et Cosmochimica Acta* 218:1–26. https://doi.org/10.1016/J.GCA.2017.08.037.

Hernández-Sánchez M. T., LaRowe D. E., Deng F., Homoky W. B., Browning T. J., Martin P., Mills R. A., and Pancost R. D. 2014. Further insights into how sediment redox status controls the preservation and composition of sedimentary biomarkers. *Organic Geochemistry* 76:220–234. https://doi.org/10.1016/J.ORGGEOCHEM.2014.08.006.

Hess S. L., Henry R. M., Leovy C. B., Ryan J. A., and Tillman J. E. 1977. Meteorological results from the surface of Mars: Viking 1 and 2. *Journal of Geophysical Research* 82:4559–4574. https://doi.org/10.1029/JS082i028p04559.

Hicks L. J., Bridges J. C., and Gurman S. J. 2014. Ferric saponite and serpentine in the nakhlite Martian meteorites. *Geochimica et Cosmochimica Acta* 136:194–210. https://doi.org/10.1016/J.GCA.2014.04.010.

Hidaka H., Yoneda S., and Nishiizumi K. 2009. Cosmic-ray exposure histories of Martian meteorites studied from neutron capture reactions of Sm and Gd isotopes. *Earth and Planetary Science Letters* 288:564–571. https://doi.org/10.1016/J.EPSL.2009.10.019.

Hirschmann M. M. and Withers A. C. 2008. Ventilation of CO_2 from a reduced mantle and consequences for the early Martian greenhouse. *Earth and Planetary Science Letters* 270:147–155. https://doi.org/10.1016/J.EPSL.2008.03.034.

Hoagland D. 1938. *The water-culture method for growing plants without soil* (Circular [California Agricultural Experiment Station], 347 ed.). Berkeley, California: University of California.

Holloway J. R. 1984. Graphite-CH_4-H_2O-CO_2 equilibria at low-grade metamorphic conditions. *Geology* 12:455. https://doi.org/10.1130/0091-7613(1984) 12 < 455: GEALMC > 2.0.CO;2.

Honnons S. and Porcher J. M. 2000. In vivo experimental model for silicosis. *Journal of Environmental Pathology, Toxicology and Oncology: Official Organ of the International Society for Environmental Toxicology and Cancer* 19:391–400.

Horgan B. and Anderson R. B. 2018. Possible lacustrine carbonates in Jezero Crater, Mars—A candidate Mars 2020 landing site (abstract #1749). 49th Lunar and Planetary Science Conference. CD-ROM.

Horgan B. and Bell J. F. III 2012. Widespread weathered glass on the surface of Mars. *Geology* 40:391–394. https://doi.org/10.1130/G32755.1.

Horgan B., Bishop J. L., Christensen P. R., and Bell J. F. 2012. Potential ancient soils preserved at Mawrth Vallis from comparisons with Eastern Oregon Paleosols: Implications for early Martian climate. In *Third Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life* (abstract #1680).

Horgan B., Rice M. S., Farrand W. H., Sheldon N. D., and Bishop J. L. 2015. Possible microbial energy pathways from iron and sulfur redox gradients at Mawrth Vallis and Gale Crater, Mars. In *Astrobiology Science Conference* (abstract #7463).

Horgan B. H. N., Smith R. J., Cloutis E. A., Mann P., and Christensen P. R. 2017. Acidic weathering of basalt and basaltic glass: 1. Near-infrared spectra, thermal infrared spectra, and implications for Mars. *Journal of Geophysical Research: Planets* 122:172–202. https://doi.org/10.1002/2016je005111

Horneck G., Walter N., Westall F., Grenfell J. L., Martin W. F., Gomez F., Leuko S., Lee N., Onofri S., Tsiganis K., Saladino R., Pilat-Lohinger E., Palomba E., Harrison J., Rull F., Muller C., Strazzulla G., Brucato J. R., Rettberg P., and Capria M. T. 2016. AstRoMap European astrobiology roadmap. *Astrobiology* 16:201–243. https://doi.org/10.1089/ast.2015.1441.

Horodyskyj L. B., White T. S., and Kump L. R. 2012. Substantial biologically mediated phosphorus depletion from the surface of a Middle Cambrian paleosol. *Geology* 40:503–506. https://doi.org/10.1130/G32761.1.

Horvath D. G. and Andrews-Hanna J. C. 2017. Reconstructing the past climate at Gale crater, Mars, from hydrological modeling of late-stage lakes. *Geophysical Research Letters* 44:8196–8204. https://doi.org/10.1002/2017GL074654.

Hu R., Kass D. M., Ehlmann B. L., and Yung Y. L. 2015. Tracing the fate of carbon and the atmospheric evolution of Mars. *Nature Communications* 6:10,003. https://doi.org/10.1038/ncomms10003.

Hug L. A., Thomas B. C., Brown C. T., Frischkorn K. R., Williams K. H., Tringe S. G., and Banfield J. F. 2015. Aquifer environment selects for microbial species cohorts in sediment and groundwater. *The ISME Journal* 9:1846–1856. https://doi.org/10.1038/ismej.2015.2.

Humayun M., Nemchin A., Zanda B., Hewins R. H., Grange M., Kennedy A., Lorand J.-P., Göpel C., Fieni C., Pont S., and Deldicque D. 2013. Origin and age of the earliest Martian crust from meteorite NWA 7533. *Nature* 503:513–516. https://doi.org/10.1038/nature12764.

Hurowitz J. A., McLennan S. M., Tosca N. J., Arvidson R. E., Michalski J. R., Ming D. W., Schröder C., and Squyres S. W. 2006. In situ and experimental evidence for acidic weathering of rocks and soils on Mars. *Journal of Geophysical Research: Planets* 111. https://doi.org/10.1029/2005je002515

Hurowitz J. A., Fischer W. W., Tosca N. J., and Milliken R. E. 2010. Origin of acidic surface waters and the evolution of atmospheric chemistry on early Mars. *Nature Geoscience* 3:323–326. https://doi.org/10.1038/ngeo831.

Hurowitz J. A., Grotzinger J. P., Fischer W. W., McLennan S. M., Milliken R. E., Stein N., Vasavada A. R., Blake D. F., Dehouck E., Eigenbrode J. L., Fairén A. G., Frydenvang J., Gellert R., Grant J. A., Gupta S., Herkenhoff K. E., Ming D. W., Rampe E. B., Schmidt M. E., Siebach K. L., Stack-Morgan K., Sumner D. Y., and Wiens R. C. 2017. Redox stratification of an ancient lake in Gale crater, Mars. *Science* 356.

ICE-WG. 2015. *ISRU & Civil Engineering Needs for Future Human Mars Missions*. Report by the ISRU and Civil Engineering Working Group (ICE-WG), Chaired by S. Hoffman and R. Mueller, posted December 2015 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

ISECG. 2018. *The Global Exploration Roadmap January 2018*. Report by the International Space Exploration Coordination Group (ISECG). Retrieved from https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf

Ivanov B. A. 2001. *Mars/Moon cratering rate ratio estimates*. Dordrecht, Netherlands: Springer. pp. 87–104. https://doi.org/10.1007/978-94-017-1035-0_4

Jakosky B. M. and Phillips R. J. 2001. Mars' volatile and climate history. *Nature* 412:237–244. https://doi.org/10.1038/35084184.

Jakosky B. M., Pepin R. O., Johnson R. E., and Fox J. L. 1994. Mars atmospheric loss and isotopic fractionation by solar-wind-induced sputtering and photochemical escape. *Icarus* 111:271–288. https://doi.org/10.1006/ICAR.1994.1145.

Jakosky B. M., Grebowsky J. M., Luhmann J. G., and Brain D. A. 2015. Initial results from the MAVEN mission to Mars. *Geophysical Research Letters* 42:8791–8802. https://doi.org/10.1002/2015GL065271.

Jakus A. E., Koube K. D., Geisendorfer N. R., and Shah R. N. 2017. Robust and elastic lunar and Martian structures from 3D-printed regolith inks. *Scientific Reports* 7:44,931. https://doi.org/10.1038/srep44931.

Johnson N. M., Elsila J. E., Kopstein M., and Nuth J. A. 2012. Carbon isotopic fractionation in Fischer-Tropsch-type reactions and relevance to meteorite organics. *Meteoritics & Planetary Science* 47:1029–1034. https://doi.org/10.1111/j.1945-5100.2012.01370.x.

Johnson S. S., Mischna M. A., Grove T. L., and Zuber M. T. 2008. Sulfur-induced greenhouse warming on early Mars. *Journal of Geophysical Research* 113:E08005. https://doi.org/10.1029/2007JE002962.

Johnson S. S., Zaikova E., Goerlitz D. S., Bai Y., and Tighe S. W. 2017. Real-time DNA sequencing in the Antarctic dry valleys using the Oxford Nanopore Sequencer. *Journal of Biomolecular Techniques* 28:2–7. https://doi.org/10.7171/jbt.17-2801-009.

Johnsson M. J. 1993. The system controlling the composition of clastic sediments. *Special Paper of the Geological Society of America* 284:1–20. https://doi.org/10.1130/spe284-p1

Jones B. and Renaut R. W. 2007. Microstructural changes accompanying the opal-A to opal-CT transition: New evidence from the siliceous sinters of Geysir, Haukadalur, Iceland. *Sedimentology* 54:921–948. https://doi.org/10.1111/j.1365-3091.2007.00866.x.

Jones B. and Renaut R. W. 2012. Facies architecture in depositional systems resulting from the interaction of acidic springs, alkaline springs, and acidic lakes: Case study of Lake Roto-a-Tamaheke, Rotorua, New Zealand. *Canadian Journal of Earth Sciences* 49:1217–1250. https://doi.org/10.1139/e2012-050.

Jones J. H. 1989. Isotopic relationships among the shergottites, the nakhlites and Chassigny. Proceedings, 19th Lunar and Planetary Science Conference. pp. 465–474.

Jones J. H. 2015. Various aspects of the petrogenesis of the Martian shergottite meteorites. *Meteoritics & Planetary Science* 50:674–690. https://doi.org/10.1111/maps.12421.

Kallmeyer J., Pockalny R., Adhikari R. R., Smith D. C., and D'Hondt S. 2012. Global distribution of microbial abundance and biomass in subseafloor sediment. *Proceedings of the National Academy of Sciences* 109:16,213–16,216. https://doi.org/10.1073/pnas.1203849109.

Keil R. G., Montluçon D. B., Prahl F. G., and Hedges J. I. 1994. Sorptive preservation of labile organic matter in marine sediments. *Nature* 370:549–552. https://doi.org/10.1038/370549a0.

Keller J. M., Boynton W. V., Karunatillake S., Baker V. R., Dohm J. M., Evans L. G., Finch M. J., Hahn B. C., Hamara D. K., Janes D. M., Kerry K. E., Newsom H. E., Reedy R. C., Sprague A. L., Squyres S. W., Starr R. D., Taylor G. J., and Williams R. M. S. 2006. Equatorial and midlatitude distribution of chlorine measured by Mars Odyssey GRS. *Journal of Geophysical Research* 112: E03S08. https://doi.org/10.1029/2006je002679

Kelts K. 1988. Environments of deposition of lacustrine petroleum source rocks: An introduction. *Geological Society, London, Special Publications* 40:3–26. https://doi.org/10.1144/GSL.SP.1988.040.01.02.

Kerber L., Head J. W., Madeleine J.-B., Forget F., and Wilson L. 2012. The dispersal of pyroclasts from ancient explosive volcanoes on Mars: Implications for the friable layered deposits. *Icarus* 219:358–381. https://doi.org/10.1016/J.ICARUS.2012.03.016.

Kerber L., Dickson J. L., Head J. W., and Grosfils E. B. 2017. Polygonal ridge networks on Mars: Diversity of morphologies and the special case of the Eastern Medusae Fossae Formation. *Icarus* 281:200–219. https://doi.org/10.1016/j.icarus.2016.08.020.

Khan A. and Connolly J. A. D. 2008. Constraining the composition and thermal state of Mars from inversion of geophysical data. *Journal of Geophysical Research* 113: E07003. https://doi.org/10.1029/2007JE002996.

Khan A., Liebske C., Rozel A., Rivoldini A., Nimmo F., Connolly J. A. D., Pleasa A.-C., and Giardini D. 2018. A geophysical perspective on the bulk composition of Mars. *Journal of Geophysical Research: Planets* 123:575–611. https://doi.org/10.1002/2017JE005371.

Killops S. D. and Killops V. J. 2005. *Introduction to organic geochemistry*. Hoboken, New Jersey: Wiley-Blackwell.

Kim M. H. Y., Thibeault S. A., Simonsen L. C., and Wilson J. W. 1998. Comparison of Martian meteorites and Martian regolith as shield materials for galactic cosmic rays. NASA Technical Report Document ID# 19980237030. Report/Patent #: NASA/TP-1998-208724, NAS 1.60:208724, L-17722, Hampton, Virginia. NASA Langley Research Center.

King P. L. and McLennan S. M. 2010. Sulfur on Mars. *Elements* 6:107–112. https://doi.org/10.2113/gselements.6.2.107.

Klein F., Bach W., and McCollom T. M. 2013. Compositional controls on hydrogen generation during serpentinization of ultramafic rocks. *Lithos* 178:55–69. https://doi.org/10.1016/J.LITHOS.2013.03.008.

Klein H. P. 1978. The Viking biological experiments on Mars. *Icarus* 34:666–674. https://doi.org/10.1016/0019-1035(78)90053-2.

Kleine T., Münker C., Mezger K., and Palme H. 2002. Rapid accretion and early core formation on asteroids and theterrestrial planets from Hf–W chronometry. *Nature* 418:952–955. https://doi.org/10.1038/nature00982.

Kleinhenz J. E. and Paz A. 2017. An ISRU propellant production system for a fully fueled Mars Ascent Vehicle. In *10th Symposium on Space Resource Utilization*. Reston, Virginia: American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2017-0423

Kminek G., Conley C., Allen C. C., Bartlett D. H., Beaty D. W., Benning L. G., Bhartia R., Boston P. J., Duchaine C., Farmer J. D., Flynn G. J., Glavin D. P., Gorby Y., Hallsworth J. E., Mogul R., Moser D., Price P. B., Pukall R., Fernandez-Remolar D., Smith C. L., Stedman K., Steele A., Stepanauskas R., Sun H., Vago J. L., Voytek M. A., Weiss P. S., and Westall F. 2014. Report of the workshop for life detection in samples from Mars. *Life Sciences in Space Research* 2:1–5. https://doi.org/10.1016/J.LSSR.2014.05.001.

Kminek G., Conley C., Hipkin V., and Yano H. 2017. COSPAR's planetary protection policy. *Space Research Today* 200:12–25. https://doi.org/10.1016/J.SRT.2017.11.010.

Kminek G, Clark B. C., Conley C. A., Jones M. A., Patel M., Race M. S., Rucker M. A., Santolik O., Siegel B., and Spry J. A. 2018. Report of the COSPAR workshop on Refining Planetary Protection Requirements for Human Missions. https://planetaryprotection.nasa.gov/file_download/133/Report+COSPAR+workshop+refining+planetary+protection+requirements+for+human+missions+final20180424.pdf

Knowlton C., Veerapaneni R., D'Elia T., and Rogers S. 2013. Microbial analyses of ancient ice core sections from Greenland and Antarctica. *Biology* 2:206–232. https://doi.org/10.3390/biology2010206.

Konhauser K. O., Jones B., Reysenbach A.-L., and Renaut R. W. 2003. Hot spring sinters: Keys to understanding Earth's earliest life forms. *Canadian Journal of Earth Sciences* 40:1713–1724. https://doi.org/10.1139/e03-059.

Kounaves S. P., Chaniotakis N. A., Chevrier V. F., Carrier B. L., Folds K. E., Hansen V. M., McElhone K. M., O'Neil G. D., and Weber A. W. 2014a. Identification of the perchlorate parent salts at the Phoenix Mars landing site and possible implications. *Icarus* 232:226–231. https://doi.org/10.1016/J.ICARUS.2014.01.016.

Kounaves S. P., Carrier B. L., O'Neil G. D., Stroble S. T., and Claire M. W. 2014b. Evidence of Martian perchlorate, chlorate, and nitrate in Mars meteorite EETA79001: Implications for oxidants and organics. *Icarus* 229:206–213. https://doi.org/10.1016/J.ICARUS.2013.11.012.

Kozich J. J., Westcott S. L., Baxter N. T., Highlander S. K., and Schloss P. D. 2013. Development of a dual-index sequencing strategy and curation pipeline for analyzing amplicon sequence data on the MiSeq Illumina sequencing platform. *Applied and Environmental Microbiology* 79:5112–5120. https://doi.org/10.1128/AEM.01043-13.

Kraal E. R., Van Dijk M., Postma G., and Kleinhans M. G. 2008. Martian stepped-delta formation by rapid water release. *Nature* 451:973–976. https://doi.org/10.1038/nature06615.

Kral T. A. and Altheide S. T. 2013. Methanogen survival following exposure to desiccation, low pressure and Martian regolith analogs. *Planetary and Space Science* 89:167–171. https://doi.org/10.1016/J.PSS.2013.09.010.

Kral T. A., Goodhart T. H., Harpool J. D., Hearnsberger C. E., McCracken G. L., and McSpadden S. W. 2016. Sensitivity and adaptability of methanogens to perchlorates: Implications for life on Mars. *Planetary and Space Science* 120:87–95. https://doi.org/10.1016/J.PSS.2015.11.014.

Kremer C. H., Bramble M. S., and Mustard J. F. 2018. Origin and emplacement of the circum-isidis olivine-rich unit (abstract #1545). 49th Lunar and Planetary Science Conference. CD-ROM.

Kronyak R. E., Kah L. C., Fedo C. M., Stack K. M., Edgett K. S., and Siebach K. L. 2017. Capping units of the Murray Formation, Gale Crater, Mars: Salsberry Peak as a Pre-Stimson Formation Caprock (abstract #1523). 48th Lunar and Planetary Science Conference. CD-ROM.

Kruijer T. S., Kleine T., Borg L. E., Brennecka G. A., Irving A. J., Bischoff A., and Agee C. B. 2017. The early differentiation of Mars inferred from Hf–W chronometry. *Earth and Planetary Science Letters* 474:345–354. https://doi.org/10.1016/J.EPSL.2017.06.047.

Kühn M. 2004. *Reactive flow modeling of hydrothermal systems*, vol. 103. Berlin, Heidelberg: Springer, Berlin Heidelberg. https://doi.org/10.1007/b13902.

LADTAG (Lunar Airborne Dust Toxicity Assessment Group). 2013. Lunar Dust Toxicity: Final Report. Dated September 26, 2013. https://humanresearchroadmap.nasa.gov/gaps/closureDocumentation/Lunar%20Dust%20Toxicity%20FINAL%20REPORT.pdf?rnd=0.157545329144944.

Lakatos H. F., Burgess H. A., Thatcher T. H., Redonnet M. R., Hernady E., Williams J. P., and Sime P. J. 2006. Oropharyngeal aspiration of a silica suspension produces a superior model of silicosis in the mouse when compared to intratracheal instillation. *Experimental Lung Research* 32:181–199. https://doi.org/10.1080/01902140600817465.

Lam C., Scully R. R., Zhang Y., Renne R. A., Hunter R. L., McCluskey R. A., Chen B. T., Castranova V., Driscoll K. E., Gardner D. E., McClellan R. O., Cooper B. L., McKay D. S., Marshall L., and James J. T. 2013. Toxicity of lunar dust assessed in inhalation-exposed rats. *Inhalation Toxicology* 25:661–678. https://doi.org/10.3109/08958378.2013.833660.

Landis G. A. 2007. Materials refining on the Moon. *Acta Astronautica* 60:906–915. https://doi.org/10.1016/j.actaastro.2006.11.004.

Lanza N. L., Wiens R. C., Arvidson R. E., Clark B. C., Fischer W. W., Gellert R., Grotzinger J. P., Hurowitz J. A., McLennan S. M., Morris R. V., Rice M. S., Bell J. F., Berger J. A., Blaney D. L., Bridges N. T., Calef F., Campbell J. L., Clegg S. M., Cousin A., Edgett K. S., Fabre C., Fisk M. R., Forni O., Frydenvang J., Hardy K. R., Hardgrove C., Johnson J. R., Lasue J., Le Mouélic S., Malin M. C., Mangold N., Martın-Torres J., Maurice S., McBride M. J., Ming D. W., Newsom H. E., Ollila A. M., Sautter V., Schröder S., Thompson L. M., Treiman A. H., Van Bommel S., Vaniman D. T., and Zorzano M.-P. 2016. Oxidation of manganese in an ancient aquifer, Kimberley formation, Gale crater, Mars. *Geophysical Research Letters* 43:7398–7407. https://doi.org/10.1002/2016GL069109.

Lapen T. J., Righter M., Brandon A. D., Debaille V., Beard B. L., Shafer J. T., and Peslier A. H. 2010. A younger age for ALH84001 and its geochemical link to shergottite sources in Mars. *Science* 328:347–351. https://doi.org/10.1126/science.1185395.

Lapen T. J., Righter M., Andreasen R., Irving A. J., Satkoski A. M., Beard B. L., Nishiizumi K., Timothy Jull A. J., and Caffee M. W. 2017. Two billion years of magmatism recorded from a single Mars meteorite ejection site. *Science Advances* 3:e1600922. https://doi.org/10.1126/sciadv.1600922.

Lasne J., Noblet A., Szopa C., Navarro-González R., Cabane M., Poch O., Stalport F., François P., Atreva S. K., and Coll P. 2016. Oxidants at the surface of Mars: A review in light of recent exploration results. *Astrobiology* 16:977–996. https://doi.org/10.1089/ast.2016.1502.

Lee T. S., Lee J., and Yong Ann K. 2015. Manufacture of polymeric concrete on the Moon. *Acta Astronautica* 114:60–64. https://doi.org/10.1016/J.ACTAASTRO.2015.04.004.

Le Roux J. P. and Rojas E. M. 2007. Sediment transport patterns determined from grain size parameters: Overview and state of the art. *Sedimentary Geology* 202:473–488. https://doi.org/10.1016/J.SEDGEO.2007.03.014.

Leshin L. A. and Vicenzi E. 2006. Aqueous processes recorded by Martian meteorites: Analyzing Martian water on Earth. *Elements* 2:157–162. https://doi.org/10.2113/gselements.2.3.157

Leshin L. A., Mahaffy P. R., Webster C. R., Cabane M., Coll P., Conrad P. G., Archer P. D. Jr., Atreya S. K., Brunner A. E., Buch A., Eigenbrode J. L., Flesch G. J., Franz H. B., Freissinet C., Glavin D. P., McAdam A. C., Miller K. E., Ming D. W., Morris R. V., Navarro-González R., Niles P. B., Owen T., Pepin R. O., Squyres S., Steele A., Stern J. C., Summons R. E., Sumner D. Y., Sutter B., Szopa C., Teinturier S., Trainer M. G., Wray J. J., Grotzinger J. P., and MSL Science Team. 2013. Volatile, isotope, and organic analysis of Martian fines with the Mars Curiosity rover. *Science* 341:1238937. https://doi.org/10.1126/science.1238937.

Levin G. V. and Straat P. A. 2016. The case for extant life on Mars and its possible detection by the Viking labeled release experiment. *Astrobiology* 16:798–810. https://doi.org/10.1089/ast.2015.1464.

Levison H. F., Dones L., Chapman C. R., Stern S. A., Duncan M. J., and Zahnle K. 2001. Could the lunar "Late Heavy Bombardment" have been triggered by the formation of Uranus and Neptune? *Icarus* 151:286–306. https://doi.org/10.1006/ICAR.2001.6608.

Lewis J. M. T., Watson J. S., Najorka J., Luong D., and Sephton M. A. 2015. Sulfate minerals: A problem for the detection of organic compounds on Mars? *Astrobiology* 15:247–258. https://doi.org/10.1089/ast.2014.1160.

Lewis J. M. T., Najorka J., Watson J. S., and Sephton M. A. 2018. The search for Hesperian organic matter on Mars: Pyrolysis studies of sediments rich in sulfur and iron. *Astrobiology* 18:454–464. https://doi.org/10.1089/ast.2017.1717.

Lewis K. W., Aharonson O., Grotzinger J. P., Kirk R. L., McEwen A. S., and Suer T.-A. 2008. Quasi-periodic bedding in the sedimentary rock record of Mars. *Science* 322:1532–1535. https://doi.org/10.1126/science.1161870.

Leya I. and Masarik J. 2013. Thermal neutron capture effects in radioactive and stable nuclide systems. *Meteoritics & Planetary Science* 48:665–685. https://doi.org/10.1111/maps.12090.

L'Haridon J., Mangold N., Meslin P.-Y., Johnson J. R., Rapin W., Forni O., Cousin A., Payré V., Dehouck E., Nachon M., Le Deit L., Gasnault O., Maurice S., and Wiens R. C. 2018. Chemical variability in mineralized veins observed by ChemCam on the lower slopes of Mount Sharp in Gale crater, Mars. *Icarus* 311:69–86. https://doi.org/10.1016/J.ICARUS.2018.01.028.

Lichtenberg K. A., Arvidson R. E., Morris R. V., Murchie S. L., Bishop J. L., Fernandez Remolar D., Glotch T. D., Dobrea E. N., Mustard J. F., Andrews-Hanna J., and Roach L. H. 2010. Stratigraphy of hydrated sulfates in the sedimentary deposits of Aram Chaos, Mars. *Journal of Geophysical Research* 115:E00D17. https://doi.org/10.1029/2009je003353

Litvak M. L., Mitrofanov I. G., Sanin A. B., Lisov D., Behar A., Boynton W. V., Deflores L., Fedosov F., Golovin D., Hardgrove C., Harshman K., Jun I., Kozyrev A. S., Kuzmin R. O., Malakhov A., Milliken R., Mischna M., Moersch J., Mokrousov M., Nikiforov S., Shvetsov V. N., Stack K., Starr R., Tate C., Tret'yakov V. I., Vostrukhin A., and MSL Science Team. 2014. Local variations of bulk hydrogen and chlorine-equivalent neutron absorption content measured at the contact between the Sheepbed and Gillespie Lake units in Yellowknife Bay, Gale Crater, using the DAN instrument onboard Curiosity. *Journal of Geophysical Research: Planets* 119:1259–1275. https://doi.org/10.1002/2013JE004556.

Liu Y., Beaty D., and Farley K. 2014a. Mars returned sample science: Planning considerations related to the inorganic contamination of geological samples. In *2014 GSA Annual Meeting*. Vancouver, British Columbia. https://gsa.confex.com/gsa/2014AM/webprogram/Paper248635.html

Liu Y., Mellon M. T., Ming D. W., Morris R. V., Noble S. K., Sullivan R., Taylor L. A., and Beaty D. W. 2014b. Planning considerations related to collecting and analyzing samples of the Martian soils (abstract #1371). 8th International Mars Conference. CD-ROM.

Loizeau D., Mangold N., Poulet F., Bibring J.-P., Bishop J. L., Michalski J., and Quantin C. 2015. History of the clay-rich unit at Mawrth Vallis, Mars: High-resolution mapping of a candidate landing site. *Journal of Geophysical Research: Planets* 120:1820–1846. https://doi.org/10.1002/2015JE004894.

Lovelock J. E. and Kaplan I. R. 1975. Thermodynamics and the recognition of alien biospheres [and discussion]. *Proceedings of the Royal Society B: Biological Sciences* 189:167–181. https://doi.org/10.1098/rspb.1975.0051.

Lowe D. R. and Byerly G. R. 1986. Early Archean silicate spherules of probable impact origin, South Africa and Western Australia. *Geology* 14:83. https://doi.org/10.1130/0091-7613(1986) 14 < 83:EASSOP > 2.0.CO;2.

Lunn G., Stutte G., Spencer L., Hummerick M., Wong L., and Wheeler R. 2017. Recovery of nutrients from inedible biomass of tomato and pepper to recycle fertilizer. Proceedings 47th International Conference on Environmental Systems ICES (p. 060). https://ttu-ir.tdl.org/ttu-ir/handle/2346/72894

Lynne B. Y. and Campbell K. A. 2003. Diagenetic transformations (opal-A to quartz) of low- and mid-temperature microbial textures in siliceous hot-spring deposits, Taupo Volcanic Zone, New Zealand. *Canadian Journal of Earth Sciences* 40:1679–1696. https://doi.org/10.1139/e03-064.

Mackelprang R., Burkert A., Haw M., Mahendrarajah T., Conaway C. H., Douglas T. A., and Waldrop M. P. 2017. Microbial survival strategies in ancient permafrost: Insights from metagenomics. *The ISME Journal* 11:2305–2318. https://doi.org/10.1038/ismej.2017.93.

Madigan M. T., Martinko J. M., and Brock T. D. 2006. *Brock biology of microorganisms*. Upper Saddle River, New Jersey: Pearson Prentice Hall.

Mahaffy P. R., Webster C. R., Cabane M., Conrad P. G., Coll P., Atreya S. K., Arvey R., Barciniak M., Benna M., Bleacher L., Brinckerhoff W. B., Eigenbrode J. L., Carignan D., Cascia M., Chalmers R. A., Dworkin J. P., Errigo T., Everson P., Franz H., Farley R., Feng S., Frazier G., Freissinet C., Glavin D. P., Harpold D. N., Hawk D., Holmes V., Johnson C. S., Jones A., Jordan P., Kellogg J., Lewis J., Lyness E., Malespin C. A., Martin D. K., Maurer J., McAdam A. C., McLennan D., Nolan T. J., Noriega M., Pavlov A. A., Prats B., Raaen E., Sheinman O., Sheppard D., Smith J., Stern J. C., Tan F., Trainer M., Ming D. W., Morris R. V., Jones J., Gundersen C., Steele A., Wray J., Botta O., Leshin L. A., Owen T., Battel S., Jakosky B. M., Manning H., Squyres S., and Mumm E. 2012. The sample analysis at Mars investigation and instrument suite. *Space Science Reviews* 170:401–478. https://doi.org/10.1007/s11214-012-9879-z.

Mahaffy P. R., Webster C. R., Atreya S. K., Franz H., Wong M., Conrad P. G., Harpold D., Jones J. J., Leshin L. A., Manning H., Owen T., Pepin R. O., Squyres S., Trainer M., and MSL Science Team. 2013. Abundance and isotopic composition of gases in the Martian atmosphere from the Curiosity rover. *Science* 341:263–266. https://doi.org/10.1126/science.1237966.

Mahaffy P. R., Webster C. R., Stern J. C., Brunner A. E., Atreya S. K., Conrad P. G., Domagal-Goldman S., Eigenbrode J. L., Flesch G. J., Christensen L. E., Franz H. B., Freissinet C., Glavin D. P., Grotzinger J. P., Jones J. H., Leshin L. A., Malespin C., McAdam A. C., Ming D. W., Navarro-Gonzalez R., Niles P. B., Owen T., Pavlov A. A., Steele A., Trainer M. G., Williford K. H., Wray J. J., and MSL Science Team. 2015. Mars atmosphere. The imprint of atmospheric evolution in the D/H of Hesperian clay minerals on Mars. *Science* 347:412–414. https://doi.org/10.1126/science.1260291.

Malin M. C. and Edgett K. S. 2001. Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission. *Journal of Geophysical Research: Planets* 106:23,429–23,570. https://doi.org/10.1029/2000JE001455.

Manceau A., Marcus M. A., and Tamura N. 2002. Quantitative speciation of heavy metals in soils and sediments by synchrotron X-ray techniques. *Reviews in Mineralogy and Geochemistry* 49:341–428. https://doi.org/10.2138/gsrmg.49.1.341.

Manceau A., Skanthakumar S., and Soderholm L. 2014. PDF analysis of ferrihydrite: Critical assessment of the under-constrained akdalaite model. *American Mineralogist* 99:102–108. https://doi.org/10.2138/am.2014.4576.

Mangold N., Carter J., Poulet F., Dehouck E., Ansan V., and Loizeau D. 2012. Late Hesperian aqueous alteration at Majuro crater, Mars. *Planetary and Space Science* 72:18–30. https://doi.org/10.1016/J.PSS.2012.03.014.

Mangold N., Thompson L. M., Forni O., Williams A. J., Fabre C., Le Deit L., Wiens R. C., Williams R., Anderson R. B., Blaney D. L., Calef F., Cousin A., Clegg S. M., Dromart G., Dietrich W. E., Edgett K. S., Fisk M. R., Gasnault O., Gellert R., Grotzinger J. P., Kah L., Le Mouélic S., McLennan S. M., Maurice S., Meslin P.-Y., Newsom H. E., Palucis M. C., Rapin W., Sautter V., Siebach K. L., Stack K., Sumner D., and Yingst A. 2016. Composition of conglomerates analyzed by the Curiosity rover: Implications for Gale Crater crust and sediment sources. *Journal of Geophysical Research: Planets* 121:353–387. https://doi.org/10.1002/2015JE004977.

Mangold N., Dehouck E., Forni O., Fedo C., Achilles C., Bristow T., Frydevang J., Gasnault O., L'Haridon J., Le Deit L., Maurice S., McLennan S. M., Meslin P. Y., Morrison S., Newsom H. E., Rampe E., Rivera-Hernandez F., Salvatore M., and Wiens R. C. 2017. Open-system weathering at Gale Crater from the chemistry of mudstones analyzed by the Curiosity Rover. In *Fourth International Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life* (abstract # 3013).

Marshall C. P., Emry J. R., and Marshall A. O. 2011. Haematite pseudomicrofossils present in the 3.5-billion-year-old Apex Chert. *Nature Geoscience* 4: 240–243. https://doi.org/10.1038/ngeo1084

Martian Meteorite Compendium. 2017. Retrieved June 24, 2018, from https://curator.jsc.nasa.gov/antmet/mmc/

Martin P. E., Farley K. A., Baker M. B., Malespin C. A., Schwenzer S. P., Cohen B. A., Mahaffy P. R., McAdam A. C., Ming D. W., Vasconcelos P. M., and Navarro-González R. 2017. A two-step K-Ar experiment on mars: Dating the diagenetic formation of jarosite from Amazonian groundwaters. *Journal of Geophysical Research: Planets* 122:2803–2818. https://doi.org/10.1002/2017JE005445.

Martín-Torres F. J., Zorzano M.-P., Valentín-Serrano P., Harri A.-M., Genzer M., Kemppinen O., Rivera-Valentin E. G., Jun I., Wray J., Bo Madsen M., Goetz W., McEwen A. S., Hardgrove C., Renno N., Chevrier V. F., Mischna M., Navarro-González R., Martínez-Frías J., Conrad P., McConnochie T., Cockell C., Berger G., Vasavada A. R., Sumner D., and Vaniman D. 2015. Transient liquid water and water activity at Gale crater on Mars. *Nature Geoscience* 8:357–361. https://doi.org/10.1038/ngeo2412.

Martins Z. 2011. In situ biomarkers and the Life Marker Chip. *Astronomy & Geophysics* 52:1.34–1.35. https://doi.org/10.1111/j.1468-4004.2011.52134.x.

Marzo G. A., Davila A. F., Tornabene L. L., Dohm J. M., Fairén A. G., Gross C., Kneissl T., Bishop A. L., Roush T. L., and McKay C. P. 2010. Evidence for Hesperian impact-induced hydrothermalism on Mars. *Icarus* 208:667–683. https://doi.org/10.1016/J.ICARUS.2010.03.013.

Mathew K. J. and Marti K. 2001. Early evolution of Martian volatiles: Nitrogen and noble gas components in ALH84001 and Chassigny. *Journal of Geophysical Research: Planets* 106:1401–1422. https://doi.org/10.1029/2000JE001255.

Mathew K. J. and Marti K. 2002. Martian atmospheric and interior volatiles in the meteorite Nakhla. *Earth and Planetary Science Letters* 199:7–20. https://doi.org/10.1016/S0012-821X(02)00562-9.

Matthewman R., Martins Z., and Sephton M. A. 2013. Type IV kerogens as analogues for organic macromolecular materials in aqueously altered carbonaceous chondrites.

Astrobiology 13:324–333. https://doi.org/10.1089/ast.2012.0820.

McClean J. B., Merrison J. P., Iversen J. J., Madsen M. B., Araghi K., Meyen F., Pike W. T., Rapp D., Sanders G., Smith P., Voecks G., Hecht M. H., and Moxie Team. 2017. Testing the Mars 2020 Oxygen In-Situ Resource Utilization Experiment (MOXIE) HEPA Filter and Scroll Pump in Simulated Mars Conditions (abstract #2410). 48th Lunar and Planetary Science Conference. CD-ROM.

McCollom T. M. and Bach W. 2009. Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks. *Geochimica et Cosmochimica Acta* 73:856–875. https://doi.org/10.1016/J.GCA.2008.10.032.

McCollom T. M. and Seewald J. S. 2001. A reassessment of the potential for reduction of dissolved CO_2 to hydrocarbons during serpentinization of olivine. *Geochimica et Cosmochimica Acta* 65:3769–3778. https://doi.org/10.1016/S0016-7037(01)00655-X.

McCoy T. J., Sims M., Schmidt M. E., Edwards L., Tornabene L. L., Crumpler L. S., Cohen B. A., Soderblom L. A., Blaney D. L., Squyres S. W., Arvidson R. E., Rice J. W. Jr, Tréguier E., d'Uston C., Grant J. A., McSween H. Y. Jr, Golombek M. P., Haldemann A. F. C., and De Souza P. A. 2008. Structure, stratigraphy, and origin of Husband Hill, Columbia Hills, Gusev Crater, Mars. *Journal of Geophysical Research* 113:E06S03. https://doi.org/10.1029/2007je003041

McCoy T. J., Corrigan C. M., and Herd C. D. K. 2011. Combining meteorites and missions to explore Mars. *Proceedings of the National Academy of Sciences* 108:19,159–19,164. https://doi.org/10.1073/pnas.1013478108.

McCubbin F. M., Smirnov A., Nekvasil H., Wang J., Hauri E., and Lindsley D. H. 2010. Hydrous magmatism on Mars: A source of water for the surface and subsurface during the Amazonian. *Earth and Planetary Science Letters* 292:132–138. https://doi.org/10.1016/J.EPSL.2010.01.028.

McCubbin F. M., Hauri E. H., Elardo S. M., Van der Kaaden K. E., Wang J., and Shearer C. K. 2012. Hydrous melting of the Martian mantle produced both depleted and enriched shergottites. *Geology* 40:683–686. https://doi.org/10.1130/G33242.1.

McCubbin F. M., Boyce J. W., Novák-Szabó T., Santos A. R., Tartèse R., Muttik N., Domokos G., Vazquez J., Keller L. P., Moser D. E., Jerolmack D. J., Shearer C. K., Steele A., Elardo S. M., Rahman Z., Anand M., Delhaye T., and Agee C. B. 2016a. Geologic history of Martian regolith breccia Northwest Africa 7034: Evidence for hydrothermal activity and lithologic diversity in the Martian crust. *Journal of Geophysical Research: Planets* 121:2120–2149. https://doi.org/10.1002/2016JE005143.

McCubbin F. M., Boyce J. W., Srinivasan P., Santos A. R., Elardo S. M., Filiberto J., Steele A., and Shearer C. K. 2016b. Heterogeneous distribution of H_2O in the Martian interior: Implications for the abundance of H_2O in depleted and enriched mantle sources. *Meteoritics & Planetary Science* 51:2036–2060. https://doi.org/10.1111/maps.12639.

McCulloch M. T. and Wasserburg G. J. 1978. Sm-Nd and Rb-Sr chronology of continental crust formation. *Science* 200:1003–1011. https://doi.org/10.1126/science.200.4345.1003.

McEwen A. S., Ojha L., Dundas C. M., Mattson S. S., Byrne S., Wray J. J., Cull S. C., Murchie S. L., Thomas N., and Gulick V. C. 2011. Seasonal flows on warm Martian slopes. *Science* 333:740–743. https://doi.org/10.1126/science.1204816.

McKay D. S., Gibson E. K., Thomas-Keprta K. L., Vali H., Romanek C. S., Clemett S. J., Chiller X. D. F., Maechling C. R., and Zare R. N. 1996. Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. *Science* 273:924–930. https://doi.org/10.1126/SCIENCE.273.5277.924.

McKeown N. K., Bishop J. L., Wray J. J., Noe Dobrea E. Z., and Silver E. A. 2009. Textures and morphologies of phyllosilicate-bearing units at Mawrth Vallis (abstract #2433). 40th Lunar and Planetary Science Conference. CD-ROM.

McLaren P. and Bowles D. 1985. The effects of sediment transport on grain-size distributions. *SEPM Journal of Sedimentary Research* 55:457–470. https://doi.org/10.1306/212F86FC-2B24-11D7-8648000102C1865D.

McLennan S. M., Hemming S., McDaniel D. K., and Hanson G. N. 1993. Geochemical approaches to sedimentation, provenance, and tectonics. In *Processes controlling the composition of clastic sediments*, edited by Johnsson M. J. and Basu A. *Geological Society of America Special Paper* 284:21–40. https://doi.org/10.1130/spe284-p21

McLennan S. M. 2012. Geochemistry of sedimentary processes on Mars. In *Sedimentary geology of Mars*. SEPM (Society for Sedimentary Geology). pp. 119–138. https://doi.org/10.2110/pec.12.102.0119

McLennan S. M. and Grotzinger J. P. 2008. The sedimentary rock cycle of Mars. In *The Martian surface: Composition, mineralogy, and physical properties*, edited by Bell J. Cambridge: Cambridge University Press. pp. 541–577. https://doi.org/10.1017/cbo9780511536076.025

McLennan S. M., Bock B., Hemming S. R., Hurowitz J. A., Lev S. M., and McDaniel D. K. 2003. The roles of provenance and sedimentary processes in the geochemistry of sedimentary rocks. In *Geochemistry of sediments and sedimentary rocks: Evolutionary considerations to mineral deposit-forming environments*, edited by Lentz D. R. Geological Association of Canada GEOtext No. 4. pp. 7–38.

McLennan S. M., Bell J. F., Calvin W. M., Christensen P. R., Clark B. C., De Souza P. A., Farmer J., Farrand W. H., Fike D. A., Gellert R., Ghosh A., Glotch T. D., Grotzinger J. P., Hahn B., Herkenhoff K. E., Hurowitz J. A., Johnson J. R., Johnson S. S., and Yen A. 2005. Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters* 240:95–121. https://doi.org/10.1016/J.EPSL.2005.09.041.

McLennan S. M., Sephton M. A., Allen C., Allwood A. C., Barbieri R., Beaty D. W., Boston P., Carr M., Grady M., Grant J., Heber V. S., Herd C. D. K., Hofmann B., King P., Mangold N., Ori G. G., Rossi A. P., Raulin F., Ruff S. W., Sherwood Lollar B., Symes S., and Wilson M. 2012. Planning for Mars returned sample science: Final report of the MSR End-to-End International Science Analysis Group (E2E-iSAG). *Astrobiology* 12:175–230. https://doi.org/10.1089/ast.2011.0805.

McLennan S. M., Anderson R. B., Bell J. F., Bridges J. C., Calef F., Campbell J. L., Clark B. C., Clegg S., Conrad P., Cousin A., Des Marais D. J., Dromart G., Dyar M. D., Edgar L. A., Ehlmann B. L., Fabre C., Forni O., Gasnault O., Gellert R., Gordon S., Grant J. A., Grotzinger J. P., Gupta S., Herkenhoff K. E., Hurowitz J. A., King P. L., Le Mouélic S., Leshin L. A., Léveillé R., Lewis K. W., Mangold N., Maurice S., Ming D. W., Morris R. V., Nachon M., Newsom H. E., Ollila A. M., Perrett G. M., Rice M. S., Schmidt M. E., Schwenzer S. P., Stack K., Stolper E. M., Sumner D. Y., Treiman A. H., Van Bommel S., Vaniman D. T., Vasavada A., Wiens R. C., Yingst R. A., and MSL Science Team. 2014. Elemental geochemistry of sedimentary rocks at Yellowknife Bay, Gale crater, Mars. *Science* 343:1244734. https://doi.org/10.1126/science.1244734.

McSween H. Y. 2008. Martian meteorites as crustal samples. In *The Martian surface: Composition, mineralogy, and physical properties*, edited by Bell J. F.. Cambridge, UK: Cambridge University Press. pp. 383–395.

McSween H. Y. 2015. Petrology on Mars. *American Mineralogist* 100:2380–2395. https://doi.org/10.2138/am-2015-5257.

McSween H. Y. and McLennan S. M. 2014. Mars. In *Treatise on Geochemistry*. Amsterdam: Elsevier. pp. 251–300. https://doi.org/10.1016/b978-0-08-095975-7.00125-x

McSween H. Y., Grove T. L., Lentz R. C. F., Dann J. C., Holzheid A. H., Riciputi L. R., and Ryan J. G. 2001. Geochemical evidence for magmatic water within Mars from pyroxenes in the Shergotty meteorite. *Nature* 409:487–490. https://doi.org/10.1038/35054011.

McSween H. Y., Ruff S. W., Morris R. V., Bell J. F., Herkenhoff K., Gellert R., Stockstill K. R., Tornabene L. L., Squyres S. W., Crisp J. A., Christensen P. R., McCoy T. J., Mittlefehldt D. W., and Schmidt M. 2006. Alkaline volcanic rocks from the Columbia Hills, Gusev crater, Mars. *Journal of Geophysical Research* 111:E09S91. https://doi.org/10.1029/2006je002698

McSween H. Y., Taylor G. J., and Wyatt M. B. 2009. Elemental composition of the Martian crust. *Science* 324:736–739. https://doi.org/10.1126/science.1165871.

McSween H. Y., McGlynn I. O., and Rogers A. D. 2010. Determining the modal mineralogy of Martian soils. *Journal of Geophysical Research* 115:E00F12. https://doi.org/10.1029/2010je003582

Médard E. and Grove T. L. 2006. Early hydrous melting and degassing of the Martian interior. *Journal of Geophysical Research* 111:E11003. https://doi.org/10.1029/2006JE002742.

Mellon M. T., Arvidson R. E., Sizemore H. G., Searls M. L., Blaney D. L., Cull S., Hecht M. H., Heet T. L., Keller H. U., Lemmon M. T., Markiewicz W. J., Ming D. W., Morris R. V., Thomas Pike W., and Zent A. P. 2009. Ground ice at the Phoenix landing site: Stability state and origin. *Journal of Geophysical Research* 114:E00E07. https://doi.org/10.1029/2009je003417

Melwani Daswani M., Schwenzer S. P., Reed M. H., Wright I. P., and Grady M. M. 2016. Alteration minerals, fluids, and gases on early Mars: Predictions from 1-D flow geochemical modeling of mineral assemblages in meteorite ALH 84001. *Meteoritics & Planetary Science* 51:2154–2174. https://doi.org/10.1111/maps.12713.

MEPAG. 2002. Groundbreaking MSR: Science requirements and cost estimates for a first Mars surface sample return mission. http://mepag.jpl.nasa.gov/reports/index.html.

MEPAG. 2008. Science priorities for Mars sample return: The MEPAG Next Decade Science Analysis Group (ND-SAG). *Astrobiology* 8:489–535. https://doi.org/10.1089/ast.2008.0759.

MEPAG. 2010. 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). *Astrobiology* 10:127–163. https://doi.org/10.1089/ast.2010.0462.

MEPAG. 2015a. *Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015*. Hamilton V. 74 p. white paper posted June, 2015 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm

MEPAG. 2015b. Report from the Next Orbiter Science Analysis Group (NEX-SAG), Chaired by B. Campbell and R. Zurek. http://mepag.nasa.gov/reports.cfm.

Meunier A., Petit S., Ehlmann B. L., Dudoignon P., Westall F., Mas A., El Albani A., and Ferrage E. 2012. Magmatic precipitation as a possible origin of Noachian clays on Mars. *Nature Geoscience* 5:739–743. https://doi.org/10.1038/ngeo1572.

Michalski J. R., Cuadros J., Niles P. B., Parnell J., Deanne Rogers A., and Wright S. P. 2013. Groundwater activity on Mars and implications for a deep biosphere. *Nature Geoscience* 6:133–138. https://doi.org/10.1038/ngeo1706.

Michalski J. R., Cuadros J., Bishop J. L., Darby Dyar M., Dekov V., and Fiore S. 2015. Constraints on the crystal-chemistry of Fe/Mg-rich smectitic clays on Mars and links to global alteration trends. *Earth and Planetary Science Letters* 427:215–225. https://doi.org/10.1016/J.EPSL.2015.06.020.

Michalski J. R., Dobrea E. Z. N., Niles P. B., and Cuadros J. 2017. Ancient hydrothermal seafloor deposits in Eridania basin on Mars. *Nature Communications* 8:15,978. https://doi.org/10.1038/ncomms15978.

Michel F. M., Ehm L., Antao S. M., Lee P. L., Chupas P. J., Liu G., Strongin D. R., Schoonen M. A. A., Phillips B. L., and Parise J. B. 2007. The structure of ferrihydrite, a nanocrystalline material. *Science* 316:1726–1729. https://doi.org/10.1126/science.1142525.

Mickol R. L. and Kral T. A. 2017. Low pressure tolerance by methanogens in an aqueous environment: Implications for subsurface life on Mars. *Origins of Life and Evolution of Biospheres* 47:511–532. https://doi.org/10.1007/s11084-016-9519-9.

Miller H. M., Matter J. M., Kelemen P., Ellison E. T., Conrad M. E., Fierer N., Ruchala T., Tominaga M., and Templeton A. S. 2016. Modern water/rock reactions in Oman hyperalkaline peridotite aquifers and implications for microbial habitability. *Geochimica et Cosmochimica Acta* 179:217–241. https://doi.org/10.1016/J.GCA.2016.01.033.

Miller H. M., Matter J. M., Kelemen P., Ellison E. T., Conrad M., Fierer N., Ruchala T., Tominaga M., and Templeton A. S. 2017. Reply to "Methane origin in the Samail ophiolite: Comment on 'Modern water/rock reactions in Oman hyperalkaline peridotite aquifers and implications for microbial habitability'" [Geochim. Cosmochim. Acta 179 (2016) 217–241]. *Geochimica et Cosmochimica Acta* 197:471–473. https://doi.org/10.1016/J.GCA.2016.11.011.

Milliken R. E. and Bish D. L. 2010. Sources and sinks of clay minerals on Mars. *Philosophical Magazine* 90:2293–2308. https://doi.org/10.1080/14786430903575132.

Ming D. W., Archer P. D., Glavin D. P., Eigenbrode J. L., Franz H. B., Sutter B., Brunner A. E., Stern J. C., Freissinet C., McAdam A. C., Mahaffy P. R., Cabane M., Coll P., Campbell J. L., Atreya S. K., Niles P. B., Bell J. F. III, Bish D. L., Brinckerhoff W. B., Buch A., Conrad P. G., Des Marais D. J., Ehlmann B. L., Fairén A. G., Farley K., Flesch G. J., Francois P., Gellert R., Grant J. A., Grotzinger J. P., Gupta S., Herkenhoff K. E., Hurowitz J. A., Leshin L. A., Lewis K. W., McLennan S. M., Miller K. E., Moersch J., Morris R. V., Navarro-González R., Pavlov A. A., Perrett G. M., Pradler I., Squyres S. W., Summons R. E., Steele A., Stolper E. M., Sumner D. Y., Szopa C., Teinturier S., Trainer M. G., Treiman A. H., Vaniman D. T., Vasavada A. R., Webster C. R., Wray J. J., Yingst R. A., and MSL Science Team. 2014. Volatile and organic compositions of sedimentary rocks in Yellowknife Bay, Gale crater, Mars. *Science* 343:1245267. https://doi.org/10.1126/science.1245267.

Mitrofanov I. G., Litvak M. L., Kozyrev A. S., Sanin A. B., Tret'yakov V. I., Grin'kov V. Y., Boynton W. V., Shinohara C., Hamara D., and Saunders R. S. 2004. Soil water content on Mars as estimated from neutron measurements by the HEND instrument onboard the 2001 Mars Odyssey Spacecraft. *Solar System Research* 38:253–257. https://doi.org/10.1023/B:SOLS.0000037461.70809.45.

Mitrofanov I. G., Litvak M. L., Sanin A. B., Starr R. D., Lisov D. I., Kuzmin R. O., Behar A., Boynton W. V., Hardgrove C., Harshman K., Jun I., Milliken R. E., Mischna M. A., Moersch J. E., and Tate C. G. 2014. Water and chlorine content in the Martian soil along the first 1900 m of the Curiosity rover traverse as estimated by the DAN instrument. *Journal of Geophysical Research: Planets* 119:1579–1596. https://doi.org/10.1002/2013JE004553.

Mittelholz A., Morschhauser A., Johnson C. L., Langlais B., Lillis R. J., Vervelidou F., and Weiss B. P. 2018. The Mars 2020 candidate landing sites: A magnetic field perspective. *Earth and Space Science* 5:410–424. https://doi.org/10.1029/2018EA000420

Montgomery W., Bromiley G. D., and Sephton M. A. 2016. The nature of organic records in impact excavated rocks on Mars. *Scientific Reports* 6:30,947. https://doi.org/10.1038/srep30947.

Moore E. K., Jelen B. I., Giovannelli D., Raanan H., and Falkowski P. G. 2017. Metal availability and the expanding network of microbial metabolisms in the Archaean eon. *Nature Geoscience* 10:629–636. https://doi.org/10.1038/ngeo3006.

Morbidelli A. 2010. A coherent and comprehensive model of the evolution of the outer solar system. *Comptes Rendus Physique* 11:651–659. https://doi.org/10.1016/J.CRHY.2010.11.001.

Morbidelli A., Nesvorny D., Laurenz V., Marchi S., Rubie D. C., Elkins-Tanton L., Wieczorek M., and Jacobson S. 2018. The timeline of the lunar bombardment: Revisited. *Icarus* 305:262–276. https://doi.org/10.1016/J.ICARUS.2017.12.046.

Mormile M. R., Hong B.-Y., and Benison K. C. 2009. Molecular analysis of the microbial communities of Mars analog lakes in Western Australia. *Astrobiology* 9:919–930. https://doi.org/10.1089/ast.2008.0293.

Morozova D., Möhlmann D., and Wagner D. 2007. Survival of methanogenic archaea from Siberian Permafrost under simulated Martian thermal conditions. *Origins of Life and Evolution of Biospheres* 37:189–200. https://doi.org/10.1007/s11084-006-9024-7.

Morris R. V., Ruff S. W., Gellert R., Ming D. W., Arvidson R. E., Clark B. C., Golden D. C., Siebach K., Klingelhöfer G., Schröder C., Fleischer I., Yen A. S., and Squyres S. W. 2010. Identification of carbonate-rich outcrops on Mars by the Spirit rover. *Science* 329:421–424. https://doi.org/10.1126/science.1189667.

Morris R. V., Vaniman D. T., Blake D. F., Gellert R., Chipera S. J., Rampe E. B., Ming D. W., Morrison S. M., Downs R. T., Treiman A. H., Yen A. S., Grotzinger J. P., Achilles C. N., Bristow T. F., Crisp J. A., Des Marais D. J., Farmer J. D., Fendrich K. V., Frydenvang J., Graff T. G., Morookian J. M., Stolper E. M., and Schwenzer S. P. 2016. Silicic volcanism on Mars evidenced by tridymite in high-SiO_2 sedimentary rock at Gale crater. *Proceedings of the National Academy of Sciences* 113:7071–7076. https://doi.org/10.1073/pnas.1607098113.

Morrison S. M., Downs R. T., Blake D. F., Vaniman D. T., Ming D. W., Hazen R. M., Treiman A. H., Achilles C. N., Yen A. S., Morris R. V., Rampe E. B., Bristow T. F., Chipera S. J., Sarrazin P. C., Gellert R., Fendrich K. V., Morookian J. M., Farmer J. D., Des Marais D. J., and Craig P. I. 2018. Crystal chemistry of Martian minerals from Bradbury Landing through Naukluft Plateau, Gale crater, Mars. *American Mineralogist* 103:857–871. https://doi.org/10.2138/am-2018-6124.

Morschhauser A., Grott M., and Breuer D. 2011. Crustal recycling, mantle dehydration, and the thermal evolution of Mars. *Icarus* 212:541–558. https://doi.org/10.1016/J.ICARUS.2010.12.028.

Moser D. E. 1997. Dating the shock wave and thermal imprint of the giant Vredefort impact, South Africa. *Geology* 25:7. https://doi.org/10.1130/0091-7613(1997)025 < 0007:DTSWAT > 2.3.CO;2.

Moser D. E., Chamberlain K. R., Tait K. T., Schmitt A. K., Darling J. R., Barker I. R., and Hyde B. C. 2013. Solving the Martian meteorite age conundrum using micro-baddeleyite and launch-generated zircon. *Nature* 499:454–457. https://doi.org/10.1038/nature12341.

Mulkidjanian A. Y., Bychkov A. Y., Dibrova D. V., Galperin M. Y., and Koonin E. V. 2012. Origin of first cells at terrestrial, anoxic geothermal fields. *Proceedings of the National Academy of Sciences* 109:E821–30. https://doi.org/10.1073/pnas.1117774109.

Murchie S. L., Mustard J. F., Ehlmann B. L., Milliken R. E., Bishop J. L., McKeown N. K., Noe Dobrea E. Z., Seelos F. P., Buczkowski D. L., Wiseman S. M., Arvidson R. E., Wray J. J., Swayze G., Clark R. N., Des Marais D. J., McEwen A. S., and Bibring J.-P. 2009. A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. *Journal of Geophysical Research* 114:E00D06. https://doi.org/10.1029/2009je003342

Murty S. V. S. and Mohapatra R. K. 1997. Nitrogen and heavy noble gases in ALH 84001: Signatures of ancient Martian atmosphere. *Geochimica et Cosmochimica Acta* 61:5417–5428. https://doi.org/10.1016/S0016-7037(97)00315-3.

Muscente A. D., Czaja A. D., Tuggle J., Winkler C., and Xiao S. 2018. Manganese oxides resembling microbial fabrics and their implications for recognizing inorganically preserved microfossils. *Astrobiology* 18:249–258. https://doi.org/10.1089/ast.2017.1699.

Mustard J. F., Poulet F., Head J. W., Mangold N., Bibring J.-P., Pelkey S. M., Fassett C. I., Langevin Y., and Neukum

G. 2007. Mineralogy of the Nili Fossae region with OMEGA/Mars Express data: 1. Ancient impact melt in the Isidis Basin and implications for the transition from the Noachian to Hesperian. *Journal of Geophysical Research* 112:E08S03. https://doi.org/10.1029/2006je002834

Mustard J. F., Murchie S. L., Pelkey S. M., Ehlmann B. L., Milliken R. E., Grant J. A., Bibring J.-P., Poulet F., Bishop J., Noe Dobrea E., Roach L., Seelos F., Arvidson R. E., Wiseman S., Green R., Hash C., Humm D., Malaret E., McGovern J. A., Seelos K., Clancy T., Clark R., Marais D. D., Izenberg N., Knudson A., Langevin Y., Martin T., McGuire P., Morris R., Robinson M., Roush T., Smith M., Swayze G., Taylor H., Titus T., and Wolff M. 2008. Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument. *Nature* 454:305–309. https://doi.org/10.1038/nature07097.

Mustard J. F., Ehlmann B. L., Murchie S. L., Poulet F., Mangold N., Head J. W., Bibring J.-P., and Roach L. H. 2009. Composition, morphology, and stratigraphy of Noachian crust around the Isidis basin. *Journal of Geophysical Research* 114:E00D12. https://doi.org/10.1029/2009je003349

Mustard J. F., Adler M., Allwood A., Bass D., Beaty D., Bell J. F., Brinckerhoff W. B., Carr M. H., Des Marais D. J., Drake B. G., Edgett K. S., Eigenbrode J. L., Elkins-Tanton L. T., Grant J. A., Milkovich S. M., Ming D., Moore C., Murchie S., Onstott T. C., Ruff S. W., Sephton M. A., Steele A., and Treiman A. 2013. Report of the Mars 2020 Science Definition Team. https://mepag.jpl.nasa.gov/reports/MEP/Mars_2020_SDT_Report_Final.pdf

Mykytczuk N. C. S., Foote S. J., Omelon C. R., Southam G., Greer C. W., and Whyte L. G. 2013. Bacterial growth at −15°C; molecular insights from the permafrost bacterium Planococcus halocryophilus Or1. *The ISME Journal* 7:1211–1226. https://doi.org/10.1038/ismej.2013.8.

Nachon M., Mangold N., Forni O., Kah L. C., Cousin A., Wiens R. C., Anderson R., Blaney D., Blank J. G., Calef F., Clegg S. M., Fabre C., Fisk M. R., Gasnault O., Grotzinger J. P., Kronyak R., Lanza N. L., Lasue J., and Sumner D. 2017. Chemistry of diagenetic features analyzed by ChemCam at Pahrump Hills, Gale crater, Mars. *Icarus* 281:121–136. https://doi.org/10.1016/J.ICARUS.2016.08.026.

NASA (National Aeronautics and Space Administration). 2009. Human exploration of Mars: Design reference architecture 5.0 (NASA Publication No. NASA-SP-2009-566). http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf.

NASA (National Aeronautics and Space Administration). 2012. NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions. NPI 8020.7/NPD 8020.7G. https://nodis3.gsfc.nasa.gov/OPD_docs/NPI_8020_7_.doc

NASA (National Aeronautics and Space Administration). 2014. Project Morpheus Free Flight 10, frame 2:28. Kennedy Space Center. https://www.youtube.com/watch?v=sI5tsetrbpA

NASEM (National Academies of Sciences, Engineering and Medicine). 2015. *Review of the MEPAG Report on Mars Special Regions*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/21816

Navarre-Sitchler A., Steefel C. I., Yang L., Tomutsa L., and Brantley S. L. 2009. Evolution of porosity and diffusivity associated with chemical weathering of a basalt clast. *Journal of Geophysical Research* 114:F02016. https://doi.org/10.1029/2008JF001060.

Navarre-Sitchler A., Steefel C. I., Sak P. B., and Brantley S. L. 2011. A reactive-transport model for weathering rind formation on basalt. *Geochimica et Cosmochimica Acta* 75:7644–7667. https://doi.org/10.1016/J.GCA.2011.09.033.

Navarro-González R., Vargas E., De la Rosa J., Raga A. C., and McKay C. P. 2010. Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars. *Journal of Geophysical Research* 115:E12010. https://doi.org/10.1029/2010JE003599.

Neaman A., Chorover J., and Brantley S. L. 2005. Element mobility patterns record organic ligands in soils on early Earth. *Geology* 33:117. https://doi.org/10.1130/G20687.1.

Nekvasil H., Filiberto J., McCubbin F. M., and Lindsley D. H. 2007. Alkalic parental magmas for chassignites? *Meteoritics & Planetary Science* 42:979–992. https://doi.org/10.1111/j.1945-5100.2007.tb01145.x.

Nemchin A. A., Grange M. L., Pidgeon R. T., and Meyer C. 2012. Lunar zirconology. *Australian Journal of Earth Sciences* 59:277–290. https://doi.org/10.1080/08120099.2011.613484.

Nemchin A. A., Humayun M., Whitehouse M. J., Hewins R. H., Lorand J.-P., Kennedy A., Grange B., Zanda C., Fieni C., and Deldicque D. 2014. Record of the ancient Martian hydrosphere and atmosphere preserved in zircon from a Martian meteorite. *Nature Geoscience* 7:638–642. https://doi.org/10.1038/ngeo2231.

Nesbitt H. W. 2003. Petrogenesis of siliciclastic sediments and sedimentary rocks. In *Geochemistry of sediments and sedimentary rocks: Evolutionary considerations to mineral deposit-forming environments* (Vol. GEOtext No. 4), edited by Lentz D. R. pp. 39–51. St. John's, Newfoundland: Geological Association of Canada.

Newsom H. E. 1980. Hydrothermal alteration of impact melt sheets with implications for Mars. *Icarus* 44:207–216. https://doi.org/10.1016/0019-1035(80)90066-4.

Nicholson W. L., Krivushin K., Gilichinsky D., and Schuerger A. C. 2013. Growth of *Carnobacterium spp*. from permafrost under low pressure, temperature, and anoxic atmosphere has implications for Earth microbes on Mars. *Proceedings of the National Academy of Sciences*, 110:666–671. https://doi.org/10.1073/pnas.1209793110

Niles P. B., Boynton W. V., Hoffman J. H., Ming D. W., and Hamara D. 2010. Stable isotope measurements of Martian atmospheric CO_2 at the Phoenix landing site. *Science* 329:1334–1337. https://doi.org/10.1126/science.1192863.

Noe Dobrea E. Z., McKeown N., Bishop J. L., and Silver E. 2009. Terrestrial analog studies of Mawrth Vallis, Mars: The Painted Desert (abstract #2165). 40th Lunar and Planetary Science Conference. CD-ROM.

Noe Dobrea E. Z., Bishop J. L., McKeown N. K., Fu R., Rossi C. M., Michalski J. R., Heinlein C., Hanus V., Poulet F., Mustard R. J. F., Murchie S., McEwen A. S., Swayze G., Bibring J.-P., Malaret E., and Hash C. 2010. Mineralogy and stratigraphy of phyllosilicate-bearing and dark mantling units in the greater Mawrth Vallis/west Arabia Terra area: Constraints on geological origin. *Journal of Geophysical Research* 115:E00D19. https://doi.org/10.1029/2009je003351

Noe Dobrea E. Z., McAdam A. C., Freissinet C., Franz H., Belmahdi I., Hammersley M. R., and Stoker C. R. 2016. Characterizing the mechanisms for the preservation of organics at the Painted Desert: Lessons for MSL, Exo-

Mars, and Mars 2020 (abstract #2796). 47th Lunar and Planetary Science Conference. CD-ROM.
Noonan J. P., Hofreiter M., Smith D., Priest J. R., Rohland N., Rabeder G., Krause J., Detter J. C., Pääbo S., and Rubin E. M. 2005. Genomic sequencing of Pleistocene cave bears. *Science* 309:597–599. https://doi.org/10.1126/science.1113485.
Noonan J. P., Coop G., Kudaravalli S., Smith D., Krause J., Alessi J., Chen F., Platt D., Pääbo S., Pritchard J. K., and Rubin E. M. 2006. Sequencing and analysis of Neanderthal genomic DNA. *Science* 314:1113–1118. https://doi.org/10.1126/science.1131412.
NRC (National Research Council). 1978. *Strategy for the Exploration of the Inner Planets: 1977–1987*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/12379
NRC (National Research Council). 1990a. *International Cooperation for Mars Exploration and Sample Return*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/12327
NRC (National Research Council). 1990b. *1990 Update to Strategy for Exploration of the Inner Planets*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/20304
NRC (National Research Council). 1994. *An Integrated Strategy for Planetary Sciences 1995–2010*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/9264
NRC (National Research Council). 1996. *Review of NASA's Planned Mars Program*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/12278
NRC (National Research Council). 1997. *Mars Sample Return*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/5563
NRC (National Research Council). 2002. *Safe on Mars: Precursor measurements necessary to support human operations on the Martian surface*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/10360
NRC (National Research Council). 2003. *Assessment of Mars Science and Mission Priorities*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/10715
NRC (National Research Council). 2006. *Assessment of NASA's Mars Architecture 2007–2016*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/11717
NRC (National Research Council). 2007a. *An astrobiology strategy for the exploration of Mars*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/11937
NRC (National Research Council). 2007b. *The limits of organic life in planetary systems*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/11919
NRC (National Research Council). 2009. *Assessment of planetary protection requirements for Mars sample return missions*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/12576
NRC (National Research Council). 2011. *Visions & voyages for planetary science in the decade 2013–2022*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/13117
Nutman A. P., Bennett V. C., Friend C. R. L., Van Kranendonk M. J., and Chivas A. R. 2016. Rapid emergence of life shown by discovery of 3,700-million-year-old microbial structures. *Nature* 537:535–538. https://doi.org/10.1038/nature19355.
Nyquist L. E., Bogard D. D., Shih C.-Y., Greshake A., Stöffler D., and Eugster O. 2001. Ages and geologic histories of Martian meteorites. *Space Science Reviews* 96:105–164. https://doi.org/10.1023/A:1011993105172.
Ojha L., Wilhelm M. B., Murchie S. L., McEwen A. S., Wray J. J., Hanley J., Massé M., and Chojnacki M. 2015. Spectral evidence for hydrated salts in recurring slope lineae on Mars. *Nature Geoscience* 8:829–832. https://doi.org/10.1038/ngeo2546.
Okubo C. H. and McEwen A. S. 2007. Fracture-controlled paleo-fluid flow in Candor Chasma, Mars. *Science* 315:983–985. https://doi.org/10.1126/science.1136855.
Onofri S., De Vera J.-P., Zucconi L., Selbmann L., Scalzi G., Venkateswaran K. J., Rabbow E., De La Torre R., and Horneck G. 2015. Survival of antarctic cryptoendolithic fungi in simulated Martian conditions on board the International Space Station. *Astrobiology* 15:1052–1059. https://doi.org/10.1089/ast.2015.1324.
Onstott T. C., McGown D. J., Bakermans C., Ruskeeniemi T., Ahonen L., Telling J., Soffientino B., Pfiffner S. M., Sherwood-Lollar B., Frape S., Stotler R., Johnson E. J., Vishnivetskaya T. A., Rothmel R., and Pratt L. M. 2009. Microbial communities in subpermafrost saline fracture water at the Lupin Au Mine, Nunavut, Canada. *Microbial Ecology* 58:786–807. https://doi.org/10.1007/s00248-009-9553-5.
Orlando L., Ginolhac A., Zhang G., Froese D., Albrechtsen A., Stiller M., Schubert M., Cappellini E., Petersen B., Moltke I., Johnson P. L., Fumagalli M., Vilstrup J. T., Raghavan M., Korneliussen T., Malaspinas A. S., Vogt J., Szklarczyk D., Kelstrup C. D., Vinther J., Dolocan A., Stenderup J., Velazquez A. M., Cahill J., Rasmussen M., Wang X., Min J., Zazula G. D., Seguin-Orlando A., Mortensen C., Magnussen K., Thompson J. F., Weinstock J., Gregersen K., Røed K. H., Eisenmann V., Rubin C. J., Miller D. C., Antczak D. F., Bertelsen M. F., Brunak S., Al-Rasheid K. A., Ryder O., Andersson L., Mundy J., Krogh A., Gilbert M. T., Kjær K., Sicheritz-Ponten T., Jensen L. J., Olsen J. V., Hofreiter M., Nielsen R., Shapiro B., Wang J., and Willerslev E. 2013. Recalibrating Equus evolution using the genome sequence of an early Middle Pleistocene horse. *Nature* 499:74–78. https://doi.org/10.1038/nature12323.
Orosei R., Lauro S. E., Pettinelli E., Cicchetti A., Coradini M., Cosciotti B., Di Paolo F., Flamini E., Mattei E., Pajola M., Soldovieri F., Cartacci M., Cassenti F., Frigeri A., Giuppi S., Martufi R., Masdea A., Mitri G., Nenna C., Noschese R., Restano M., and Seu R. 2018. Radar evidence of subglacial liquid water on Mars. *Science* 361:490–493. https://doi.org/10.1126/science.aar7268.
Osburn M. R., LaRowe D. E., Momper L. M., and Amend J. P. 2014. Chemolithotrophy in the continental deep subsurface: Sanford Underground Research Facility (SURF), USA. *Frontiers in Microbiology* 5:610. https://doi.org/10.3389/fmicb.2014.00610.
Osinski G. R., Tornabene L. L., Banerjee N. R., Cockell C. S., Flemming R., Izawa M. R. M., McCutcheon J., Parnell J., Preston L. J., Pickersgill A. E., Pontefract A., Sapers H. M., and Southam G. 2013. Impact-generated hydrothermal systems on Earth and Mars. *Icarus* 224:347–363. https://doi.org/10.1016/J.ICARUS.2012.08.030.
Osterloo M. M., Hamilton V. E., Bandfield J. L., Glotch T. D., Baldridge A. M., Christensen P. R., Tornabene L. L., and Anderson F. S. 2008. Chloride-bearing materials in

the southern highlands of Mars. *Science* 319:1651–1654. https://doi.org/10.1126/science.1150690.

Ott U. 1988. Noble gases in SNC meteorites: Shergotty, Nakhla, Chassigny. *Geochimica et Cosmochimica Acta* 52:1937–1948. https://doi.org/10.1016/0016-7037(88)90017-8.

Ott U. and Begemann F. 1985. Are all the "Martian" meteorites from Mars? *Nature* 317:509–512. https://doi.org/10.1038/317509a0.

Ott U., Swindle T. D., and Schwenzer S. 2018. Noble gases in Martian meteorites: Budget, sources, sinks and processes. In *Volatiles in the Martian crust*. Amsterdam: Elsevier Science Ltd. pp. 35–70.

Owen T., Maillard J. P., De Bergh C., and Lutz B. L. 1988. Deuterium on Mars: The abundance of HDO and the value of D/H. *Science* 240:1767–1767. https://doi.org/10.1126/science.240.4860.1767.

Pan L., Ehlmann B. L., Carter J., and Ernst C. M. 2017. The stratigraphy and history of Mars' northern lowlands through mineralogy of impact craters: A comprehensive survey. *Journal of Geophysical Research: Planets* 122:1824–1854. https://doi.org/10.1002/2017JE005276.

Parenteau M. N., Jahnke L. L., Farmer J. D., and Cady S. L. 2014. Production and early preservation of lipid biomarkers in iron hot springs. *Astrobiology* 14:502–521. https://doi.org/10.1089/ast.2013.1122.

Parker T. J., Gorsline D. S., Saunders R. S., Pieri D. C., and Schneeberger D. M. 1993. Coastal geomorphology of the Martian northern plains. *Journal of Geophysical Research* 98:11,061. https://doi.org/10.1029/93JE00618.

Paton M. D., Harri A.-M., Mäkinen T., and Savijärvi H. 2013. High-fidelity subsurface thermal model as part of a Martian atmospheric column model. *Geoscientific Instrumentation, Methods and Data Systems* 2:17–27. https://doi.org/10.5194/gi-2-17-2013

Pavlov A. A., Vasilyev G., Ostryakov V. M., Pavlov A. K., and Mahaffy P. 2012. Degradation of the organic molecules in the shallow subsurface of Mars due to irradiation by cosmic rays. *Geophysical Research Letters* 39. https://doi.org/10.1029/2012GL052166.

Penney D., Wadsworth C., Fox G., Kennedy S. L., Preziosi R. F., and Brown T. A. 2013. Absence of ancient DNA in sub-fossil insect inclusions preserved in 'Anthropocene' Colombian copal. *PLoS ONE* 8:e73150. https://doi.org/10.1371/journal.pone.0073150.

Pepin R. O. 2000. On the isotopic composition of primordial xenon in terrestrial planet atmospheres. *Space Science Reviews* 92:371–395. https://doi.org/10.1023/A:1005236405730.

Pepin R. O. and Porcelli D. 2002. Origin of noble gases in the terrestrial planets. *Reviews in Mineralogy and Geochemistry* 47:191–246. https://doi.org/10.2138/rmg.2002.47.7.

Perrin S. L., Bishop J. L., Parker W. G., King S. J., and Lafuente B. 2018. Mars evaporite analog site containing jarosite and gypsum at Sulfate Hill, Painted Desert, AZ (abstract #1801). 49th Lunar and Planetary Science Conference. CD-ROM.

Picard M., Hipkin V., Gingras D., Allard P., Lamarche T., Rocheleau S. G., and Gemme S. 2018. MSR fetch rover capability development at the Canadian Space Agency. In *2nd International Mars Sample Return Conference* (abstract #6123).

Plummer L. N., Bexfield L. M., and Anderholm S. K. 2003. How ground-water chemistry helps us understand the aquifer. In *U.S. Geological Survey Circular 1222*, edited by Bartolino J. R. and Cole J. C. https://water.usgs.gov/nrp/proj.bib/Publications/plummer.circ1222a.pdf

Polsgrove T., Thomas D., Sutherlin S., Stephens W., and Rucker M. 2015. Mars ascent vehicle design for human exploration. In *AIAA Space 2015* pp. AIAA2015-4416. Pasadena, California. https://ntrs.nasa.gov/search.jsp?R=20160006401

Popa R. 2014. Elusive definition of life: A survey of main ideas. In *Astrobiology: An evolutionary approach*, edited by Kolb V. M. Boca Raton, Florida: CRC Press. pp. 325–348.

Portree D. S. F. 2011. *Humans to Mars: Fifty years of mission planning, 1950-2000*. NASA History Division. https://history.nasa.gov/monograph21.pdf

Potter-McIntyre S. L., Williams J., Phillips-Landers C., and O'Connell L. 2016. Progressive diagenetic alteration of macro- and micro-scopic biosignatures in ancient springs and spring-fed lacustrine environments. In *Biosignature Preservation and Detection in Mars Analog Environments* (abstract #2005).

Poulet F., Bibring J.-P., Mustard J. F., Gendrin A., Mangold N., Langevin Y., Arvidson R. E., Gondet B., Gomez C., and The Omega Team. 2005. Phyllosilicates on Mars and implications for early Martian climate. *Nature* 438:623–627. https://doi.org/10.1038/nature04274.

Quinn D. P. and Ehlmann B. L. 2018. History of the Northeast Syrtis Sulfates, Mars, Journal of Geophysical Research (and 49th Lunar and Planetary Science Conference Abstract #1840).

Race M. S., Johnson J. E., Spry J. A., Siegel B., and Conley C. A. 2015. Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions: Workshop Report. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160012793.pdf

Rapin W., Meslin P.-Y., Maurice S., Vaniman D., Nachon M., Mangold N., Schröder S., Gasnault O., Forni O., Wiens R. C., Martínez G. M., Cousin A., Sautter V., Lasue J., Rampe E. B., and Archer D. 2016. Hydration state of calcium sulfates in Gale crater, Mars: Identification of bassanite veins. *Earth and Planetary Science Letters* 452:197–205. https://doi.org/10.1016/J.EPSL.2016.07.045.

Rapp J. F., Draper D. S., and Mercer C. M. 2013. Anhydrous liquid line of descent of Yamato-980459 and evolution of Martian parental magmas. *Meteoritics & Planetary Science* 48:1780–1799. https://doi.org/10.1111/maps.12197.

Rasmussen B. 2000. Filamentous microfossils in a 3,235-million-year-old volcanogenic massive sulphide deposit. *Nature* 405:676–679. https://doi.org/10.1038/35015063.

Reid R. P., Visscher P. T., Decho A. W., Stolz J. F., Bebout B. M., Dupraz C., Macintyre I. G., Paerl H. W., Pinckney J. L., Prufert-Bebout L., Steppe T. F., and DesMarais D. J. 2000. The role of microbes in accretion, lamination and early lithification of modern marine stromatolites. *Nature* 406:989–992. https://doi.org/10.1038/35023158.

Rempfert K. R., Miller H. M., Bompard N., Nothaft D., Matter J. M., Kelemen P., Fierer N., and Templeton A. S. 2017. Geological and geochemical controls on subsurface microbial life in the Samail ophiolite, Oman. *Frontiers in Microbiology* 8:56. https://doi.org/10.3389/fmicb.2017.00056.

Renaut R. W. and Jones B. 2011. *Hydrothermal environments, terrestrial*. Dordrecht, the Netherlands: Springer. pp. 467–479. https://doi.org/10.1007/978-1-4020-9212-1_114

Renaut R. W. and Last W. M., ed. 1994. *Sedimentology and geochemistry of modern and ancient saline lakes*. SEPM (Society for Sedimentary Geology). https://doi.org/10.2110/pec.94.50

Retallack G. J., ed. 2008. *Soils of the past*. Oxford, UK: Blackwell Science Ltd. https://doi.org/10.1002/9780470698716

Retallack G. J., Bestland E. A., and Fremd T. J. 1999. Eocene and oligocene paleosols of Central Oregon. In *Special Paper 344: Eocene and Oligocene paleosols of central Oregon*. Boulder, Colorado: Geological Society of America. pp. 1–192. https://doi.org/10.1130/0-8137-2344-2.1

Returned Sample Science Board (RSSB). 2016a. Planning for the collection of a compelling set of Mars samples in support of a potential future Mars sample return. In *2016 GSA Annual Meeting*. Denver, Colorado. https://doi.org/10.1130/abs/2016am-279910

Returned Sample Science Board (RSSB). 2016b. Recommended maximum temperature for Mars returned samples (abstract #2662). 47th Lunar and Planetary Science Conference. CD-ROM.

Returned Sample Science Board (RSSB), Beaty D. W., McSween H. Y., Carrier B. L., Czaja A. D., Goreva Y. S., Hausrath E. M., Herd C. D. K., Humayun M., McCubbin F. M., McLennan S. M., Pratt L. M., Sephton M. A., Steele A, and Weiss B. P. 2018a. Analysis of the scientific value of the Mars 2020 Spacecraft Genetic Inventory to Mars Sample Return (abstract #1202). 49th Lunar and Planetary Science Conference. CD-ROM.

Returned Sample Science Board (RSSB). 2018b. Sample quality standards for returned Martian samples. In *2nd International Mars Sample Return Conference* (abstract #6056).

Returned Sample Science Board (RSSB). 2018c. Summary of sample quality standards for returned Martian samples (abstract #1516). 49th Lunar and Planetary Science Conference. CD-ROM.

Reuter J. A., Spacek D. V., and Snyder M. P. 2015. High-throughput sequencing technologies. *Molecular Cell* 58:586–597. https://doi.org/10.1016/j.molcel.2015.05.004.

Reysenbach A.-L., Voytek M., and Mancinelli R. 2001. *Thermophiles biodiversity, ecology, and evolution*. New York: Springer.

Righter K. and Chabot N. L. 2011. Moderately and slightly siderophile element constraints on the depth and extent of melting in early Mars. *Meteoritics & Planetary Science* 46:157–176. https://doi.org/10.1111/j.1945-5100.2010.01140.x.

Righter K., Pando K., and Danielson L. R. 2009. Experimental evidence for sulfur-rich Martian magmas: Implications for volcanism and surficial sulfur sources. *Earth and Planetary Science Letters* 288:235–243. https://doi.org/10.1016/J.EPSL.2009.09.027.

Rivera-Hernandez F., Sumner D. Y., Mackey T. J., Hawes I., and Andersen D. T. 2018. In a PICL: The sedimentary deposits and facies of perennially ice-covered-lakes. *Sedimentology*. https://doi.org/10.1111/sed.12522

Rivkina E., Petrovskaya L., Vishnivetskaya T., Krivushin K., Shmakova L., Tutukina M., Meyers A., and Kondrashov F. 2016. Metagenomic analyses of the late Pleistocene permafrost—Additional tools for reconstruction of environmental conditions. *Biogeosciences* 13:2207–2219. https://doi.org/10.5194/bg-13-2207-2016.

Rogers A. D. and Nekvasil H. 2015. Feldspathic rocks on Mars: Compositional constraints from infrared spectroscopy and possible formation mechanisms. *Geophysical Research Letters* 42:2619–2626. https://doi.org/10.1002/2015GL063501.

Rogers A. D., Cowart J. C., Head J. W., Warner N. H., Palumbo A., and Golombek M. P. 2017. Properties, origins, and preservation of ancient olivine-bearing bedrock: Implications for Noachian processes on Mars. In *Fourth International Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life* (abstract #3033).

Röling W. F. M., Aerts J. W., Patty C. H. L., ten Kate I. L., Ehrenfreund P., and Direito S. O. L. 2015. The significance of microbe-mineral-biomarker interactions in the detection of life on Mars and beyond. *Astrobiology* 15:492–507. https://doi.org/10.1089/ast.2014.1276.

Rossi A. P., Neukum G., Pondrelli M., Van Gasselt S., Zegers T., Hauber E., Chicarro E., and Foing B. 2008. Large-scale spring deposits on Mars? *Journal of Geophysical Research* 113:E08016. https://doi.org/10.1029/2007JE003062.

Ruff S. W. 2017. Investigating the floor of Paleolake Jezero by way of Gusev Crater. In *Fourth International Conference on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life* (abstract #3076).

Ruff S. W. and Farmer J. D. 2016. Silica deposits on Mars with features resembling hot spring biosignatures at El Tatio in Chile. *Nature Communications* 7:13,554. https://doi.org/10.1038/ncomms13554.

Ruff S. W., Farmer J. D., Calvin W. M., Herkenhoff K. E., Johnson J. R., Morris R. V., Rice M. S., Arvidson R. E., Bell J. F. III, Christensen P. R., and Squyres S. W. 2011. Characteristics, distribution, origin, and significance of opaline silica observed by the Spirit rover in Gusev crater, Mars. *Journal of Geophysical Research* 116:E00F23. https://doi.org/10.1029/2010je003767

Ruff S. W., Niles P. B., Alfano F., and Clarke A. B. 2014. Evidence for a Noachian-aged ephemeral lake in Gusev crater, Mars. *Geology* 42:359–362. https://doi.org/10.1130/G35508.1.

Ruff S. W., Farmer J. D., and Juarez Rivera M. 2018. Testing alternative hypotheses for the origin of hydrothermal silica at Home Plate, Mars with implications for astrobiology (abstract #2367). 49th Lunar and Planetary Science Conference. CD-ROM.

Rummel J. D., Race M. S., De Vincenzi D. L., Schad P. J., Stabekis P. D., Viso M., and Acevedo S. E. 2002. *A draft test protocol for detecting possible biohazards in Martian samples returned to Earth*. Washington, DC. https://planetaryprotection.nasa.gov/summary/DraftTestProtocol

Rummel J. D., Beaty D. W., Jones M. A., Bakermans C., Barlow N. G., Boston P. J., Chevrier V. F., Clark B. C., De Vera J. P., Gough R. V., Hallsworth J. E., Head J. W., Hipkin V. J., Kieft T. L., McEwen A. S., Mellon M. T., Mikucki J. A., Nicholson W. L., Omelon C. R., Peterson R., Roden E. E., Sherwood Lollar B., Tanaka K. L., Viola D., and Wray J. J. 2014. A new analysis of Mars "Special Regions": Findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2). *Astrobiology* 14:887–968. https://doi.org/10.1089/ast.2014.1227.

Russ G. P., Burnett D. S., and Wasserburg G. J. 1972. Lunar neutron stratigraphy. *Earth and Planetary Science Letters* 15:172–186. https://doi.org/10.1016/0012-821X(72)90058-1.

Rye R. O., Back W., Hanshaw B. B., Rightmire C. T., and Pearson F. J. 1981. The origin and isotopic composition of dissolved sulfide in groundwater from carbonate aquifers in Florida and Texas. *Geochimica et Cosmochimica Acta* 45:1941–1950. https://doi.org/10.1016/0016-7037(81)90024-7.

Rye R. and Holland H. D. 2000. Life associated with a 2.76 Ga ephemeral pond? Evidence from Mount Roe #2 paleosol. *Geology* 28:483–486.

Sak P. B., Fisher D. M., Gardner T. W., Murphy K., and Brantley S. L. 2004. Rates of weathering rind formation on Costa Rican basalt. *Geochimica et Cosmochimica Acta* 68:1453–1472. https://doi.org/10.1016/J.GCA.2003.09.007.

Salvatore M. R., Mustard J. F., Head J. W., Cooper R. F., Marchant D. R., and Wyatt M. B. 2013. Development of alteration rinds by oxidative weathering processes in Beacon Valley, Antarctica, and implications for Mars. *Geochimica et Cosmochimica Acta* 115:137–161. https://doi.org/10.1016/J.GCA.2013.04.002.

Salvi S. and Williams-Jones A. E. 1997. Fischer-Tropsch synthesis of hydrocarbons during sub-solidus alteration of the Strange Lake peralkaline granite, Quebec/Labrador, Canada. *Geochimica et Cosmochimica Acta* 61:83–99. https://doi.org/10.1016/S0016-7037(96)00313-4.

Santiago-Rodriguez T. M., Patrício A. R., Rivera J. I., Coradin M., Gonzalez A., Tirado G., Cano R. G., and Toranzos G. A. 2014. *luxS* in bacteria isolated from 25- to 40-million-year-old amber. *FEMS Microbiology Letters* 350:117–124. https://doi.org/10.1111/1574-6968.12275.

Santos A. R., Agee C. B., McCubbin F. M., Shearer C. K., Burger P. V., Tartèse R., and Anand M. 2015. Petrology of igneous clasts in Northwest Africa 7034: Implications for the petrologic diversity of the Martian crust. *Geochimica et Cosmochimica Acta* 157:56–85. https://doi.org/10.1016/J.GCA.2015.02.023.

Saper L. and Mustard J. F. 2013. Extensive linear ridge networks in Nili Fossae and Nilosyrtis, Mars: Implications for fluid flow in the ancient crust. *Geophysical Research Letters* 40:245–249. https://doi.org/10.1002/grl.50106.

Sapers H. M., Osinski G. R., Banerjee N. R., and Preston L. J. 2014. Enigmatic tubular features in impact glass. *Geology* 42:471–474. https://doi.org/10.1130/G35293.1.

Sautter V., Toplis M. J., Wiens R. C., Cousin A., Fabre C., Gasnault O., Gasnault O., Maurice S., Forni O., Lasue J., Ollila A., Bridges J. C., Mangold N., Le Mouélic S., Fisk M., Meslin P.-Y., Beck P., Pinet P., Le Deit L., Rapin W., Stolper E. M., Newsom H., Dyar D., Lanza N., Vaniman D., Clegg S., and Wray J. J. 2015. In situ evidence for continental crust on early Mars. *Nature Geoscience* 8:605–609. https://doi.org/10.1038/ngeo2474.

Sautter V., Toplis M. J., Beck P., Mangold N., Wiens R., Pinet P., Cousin A., Maurice S., Le Deit L., Hewins R., Gasnault O., Quantin C., Forni O., Newsom H., Meslin P.-Y., Wray J., Bridges N., Payré V., and Le Mouélic S. 2016. Magmatic complexity on early Mars as seen through a combination of orbital, in-situ and meteorite data. *Lithos* 254–255:36–52. https://doi.org/10.1016/J.LITHOS.2016.02.023.

Schauble E. A., Rossman G. R., and Taylor H. 2003. Theoretical estimates of equilibrium chlorine-isotope fractionations. *Geochimica et Cosmochimica Acta* 67:3267–3281. https://doi.org/10.1016/S0016-7037(02)01375-3.

Scheuring R. A., Jones J. A., Novak J. D., Polk J. D., Gillis D. B., Schmid J., Duncan J. M., and Davis J. R. 2008. The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations. *Acta Astronautica* 63:980–987. https://doi.org/10.1016/J.ACTAASTRO.2007.12.065.

Schmidt M. E., Schrader C. M., and McCoy T. J. 2013. The primary fO_2 of basalts examined by the Spirit rover in Gusev Crater, Mars: Evidence for multiple redox states in the Martian interior. *Earth and Planetary Science Letters* 384:198–208. https://doi.org/10.1016/J.EPSL.2013.10.005.

Schmieder M., Kennedy T., Jourdan F., Buchner E., and Reimold W. U. 2018. A high-precision 40Ar/39Ar age for the Nördlinger Ries impact crater, Germany, and implications for the accurate dating of terrestrial impact events. *Geochimica et Cosmochimica Acta* 220:146–157. https://doi.org/10.1016/J.GCA.2017.09.036.

Schopf J. W. and Kudryavtsev A. B. 2012. Biogenicity of Earth's earliest fossils: A resolution of the controversy. *Gondwana Research* 22:761–771. https://doi.org/10.1016/J.GR.2012.07.003.

Schopf J. W., Kudryavtsev A. B., Agresti D. G., Wdowiak T. J., and Czaja A. D. 2002. Laser-Raman imagery of Earth's earliest fossils. *Nature* 416:73–76. https://doi.org/10.1038/416073a.

Schrenk M. O., Brazelton W. J., and Lang S. Q. 2013. Serpentinization, carbon, and deep life. *Reviews in Mineralogy and Geochemistry* 75:575–606. https://doi.org/10.2138/rmg.2013.75.18.

Schuerger A. C. and Clark B. C. 2008. Viking biology experiments: Lessons learned and the role of ecology in future Mars life-detection experiments. *Space Science Reviews* 135:233–243. https://doi.org/10.1007/s11214-007-9194-2.

Schuerger A. C. and Nicholson W. L. 2016. Twenty species of hypobarophilic bacteria recovered from diverse soils exhibit growth under simulated Martian conditions at 0.7 kPa. *Astrobiology* 16:964–976. https://doi.org/10.1089/ast.2016.1587

Schuerger A. C., Ulrich R., Berry B. J., and Nicholson W. L. 2013. Growth of *Serratia liquefaciens* under 7 mbar, 0°C, and CO_2—Enriched anoxic atmospheres. *Astrobiology* 13:115–131. https://doi.org/10.1089/ast.2011.0811.

Schulte M., Blake D., Hoehler T., and McCollom T. 2006. Serpentinization and its implications for life on the early Earth and Mars. *Astrobiology* 6:364–376. https://doi.org/10.1089/ast.2006.6.364.

Schulze-Makuch D., Dohm J. M., Fan C., Fairén A. G., Rodriguez J. A. P., Baker V. R., and Fink W. 2007. Exploration of hydrothermal targets on Mars. *Icarus* 189:308–324. https://doi.org/10.1016/J.ICARUS.2007.02.007.

Schwenzer S. P. and Ott U. 2006. Evaluating Kr- and Xe-data in the nakhlites and ALHA84001—Does EFA hide EFM? (abstract #1614). 37th Lunar and Planetary Science Conference. CD-ROM.

Schwenzer S. P., Ott U., Hicks L. J., Bridges J. C., Barnes G., Treiman A. H., and Swindle T. D. 2016. Fractionated noble gases in the nakhlite Martian meteorites. In *Developments in noble gas understanding and expertise #4*. 13–15. Nancy, France: CRPG. http://oro.open.ac.uk/45400/

Schwenzer S. P., Ott U., Hicks L. J., Bridges J. C., Filiberto J., Bart G. D., Swindle T. D., Miller M. A., Treiman A. H., Crowther S. A., Gilmour J. D., Herrmann S., Mohapatra R., Seidel R., Kelley S. P., Bullock M. A., Chaves C., Smith H., and Moore J. M. 2018. Fractionated Martian atmosphere—The case of the nakhlites, revisited with experiments (abstract #1561). 49th Lunar and Planetary Science Conference. CD-ROM.

Scudder N. A., Horgan B., Rutledge A. M., and Rampe E. B. 2017. Using composition to trace glacial, fluvial, and aeolian sediment transport in a Mars-analog glaciated volcanic system (abstract #2625). 48th Lunar and Planetary Science Conference. CD-ROM.

Scully R. R., Scully R. R., and Meyers V. E. 2015. *Risk of adverse health & performace effects of celestial dust exposure, in Human Research Program Space Human Factors and Habitablity (SHFH) Element*. Houston, Texas: National Aeronautics and Space Administration, Lyndon B. Johnson Space Center. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150016031.pdf

Sephton M. A. 2014. Organic geochemistry of meteorites. In *Treatise on Geochemistry* pp. 1–31. Amsterdam: Elsevier. https://doi.org/10.1016/b978-0-08-095975-7.01002-0

Sephton M. A. and Botta O. 2005. Recognizing life in the solar system: Guidance from meteoritic organic matter. *International Journal of Astrobiology* 4:269. https://doi.org/10.1017/S1473550405002806.

Sephton M. A. and Gilmour I. 2001. Compound specific isotope analysis of the organic constituents in carbonaceous chondrites. *Mass Spectrometry Reviews* 20:111–120. https://doi.org/10.1002/mas.1006.

Sephton M. A., Lewis J. M. T., Watson J. S., Montgomery W., and Garnier C. 2014. Perchlorate-induced combustion of organic matter with variable molecular weights: Implications for Mars missions. *Geophysical Research Letters* 41:7453–7460. https://doi.org/10.1002/2014GL062109.

Shaheen R., Abauanza M., Jackson T. L., McCabe J., Savarino J., and Thiemens M. H. 2013. Tales of volcanoes and El-Nino southern oscillations with the oxygen isotope anomaly of sulfate aerosol. *Proceedings of the National Academy of Sciences* 110:17,662–17,667. https://doi.org/10.1073/pnas.1213149110.

Shaheen R., Abaunza M. M., Jackson T. L., McCabe J., Savarino J., and Thiemens M. H. 2014. Large sulfur-isotope anomaly in nonvolcanic sulfate aerosol and its implications for the Archean atmosphere. *Proceedings of the National Academy of Sciences* 111:11,979–11,983. https://doi.org/10.1073/pnas.1406315111.

Shaheen R., Niles P. B., Chong K., Corrigan C. M., and Thiemens M. H. 2015a. Carbonate formation events in ALH 84001 trace the evolution of the Martian atmosphere. *Proceedings of the National Academy of Sciences* 112:336–341. https://doi.org/10.1073/pnas.1315615112.

Shaheen R., Thiemens M. H., Khachatryan A., Smirnova V., and Jackson T. L. 2015b. O-triple isotopes of primary and secondary minerals provide clues to the past and present hydrosphere of Mars: New experimental evidence. In *American Geophysical Union, Fall Meeting 2015* (abstract #P23B-2146).

Sheenan T. 1975. JSC-09432.

Sheldon N. D. and Tabor N. J. 2009. Quantitative paleoenvironmental and paleoclimatic reconstruction using paleosols. *Earth-Science Reviews* 95:1–52. https://doi.org/10.1016/J.EARSCIREV.2009.03.004.

Shih C.-Y., Nyquist L. E., Bogard D. D., McKay G. A., Wooden J. L., Bansal B. M., and Wiesmann H. 1982. Chronology and petrogenesis of young achondrites, Shergotty, Zagami, and ALHA77005: Late magmatism on a geologically active planet. *Geochimica et Cosmochimica Acta* 46:2323–2344. https://doi.org/10.1016/0016-7037(82)90205-8.

Shuster D. L. and Cassata W. S. 2015. Paleotemperatures at the lunar surfaces from open system behavior of cosmogenic 38Ar and radiogenic 40Ar. *Geochimica et Cosmochimica Acta* 155:154–171. https://doi.org/10.1016/J.GCA.2015.01.037.

Shuster D. L. and Weiss B. P. 2005. Martian surface paleotemperatures from thermochronology of meteorites. *Science* 309:594–600. https://doi.org/10.1126/science.1113077.

Siebach K. L. and Grotzinger J. P. 2014. Volumetric estimates of ancient water on Mount Sharp based on boxwork deposits, Gale Crater, Mars. *Journal of Geophysical Research: Planets* 119:189–198. https://doi.org/10.1002/2013JE004508.

Siebach K. L., Grotzinger J. P., Kah L. C., Stack K. M., Malin M., Léveillé R., and Sumner D. Y. 2014. Subaqueous shrinkage cracks in the Sheepbed mudstone: Implications for early fluid diagenesis, Gale crater, Mars. *Journal of Geophysical Research: Planets* 119:1597–1613. https://doi.org/10.1002/2014JE004623.

Siebach K. L., Grotzinger J. P., McLennan S. M., Hurowitz J. A., Ming D. W., Vaniman D. T., Rampe E. B., Blaney D. L., Kah L. C., and the MSL Science Team. 2015. Constraining the texture and composition of pore-filling cements at Gale Crater, Mars (abstract #2234). 46th Lunar and Planetary Science Conference. CD-ROM.

Sillitoe R. H. 2015. Epithermal paleosurfaces. *Mineralium Deposita* 50:767–793. https://doi.org/10.1007/s00126-015-0614-z.

Simmons S. F., Keywood M., Scott B. J., and Keam R. F. 1993. Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption. *Geology* 21:643. https://doi.org/10.1130/0091-7613(1993) 021 < 0643:ICOTRW > 2.3.CO;2.

Simpson E. L., Heness E., Bumby A., Eriksson P. G., Eriksson K. A., Hilbert-Wolf H. L., Linnevelt S., Malenda F., Modungwa T., and Okafor O. J. 2013. Evidence for 2.0Ga continental microbial mats in a paleodesert setting. *Precambrian Research* 237:36–50. https://doi.org/10.1016/j.precamres.2013.08.001.

Sinha N., Nepal S., Kral T., and Kumar P. 2017. Survivability and growth kinetics of methanogenic archaea at various pHs and pressures: Implications for deep subsurface life on Mars. *Planetary and Space Science* 136:15–24. https://doi.org/10.1016/J.PSS.2016.11.012.

Skok J. R., Mustard J. F., Ehlmann B. L., Milliken R. E., and Murchie S. L. 2010. Silica deposits in the Nili Patera caldera on the Syrtis Major volcanic complex on Mars. *Nature Geoscience* 3:838–841. https://doi.org/10.1038/ngeo990.

Slaba T C., Mertens C. J., and Blattnig S. R. 2013. *Radiation shielding optimization on Mars*. NASA Technical Report Document ID#: 20130012456

Sleep N. H., Zahnle K. J., Kasting J. F., and Morowitz H. J. 1989. Annihilation of ecosystems by large asteroid impacts on the early Earth. *Nature* 342:139–142. https://doi.org/10.1038/342139a0.

Smith P. H., Tamppari L. K., Arvidson R. E., Bass D., Blaney D., Boynton W. V., Carswell A., Catling D. C., Clark B. C., Duck T., De Jong E., Fisher D., Goetz W., Gunnlaugsson H. P., Hecht M. H., Hipkin V., Hoffman J., Hviid S. F., Keller H. U., Kounaves S. P., Lange C. F., Lemmon M. T., Madsen M. B., Markiewicz W. J., Marshall J., McKay C. P., Mellon M. T., Ming D. W., Morris R. V., Pike W. T., Renno N., Staufer U., Stoker C., Taylor P., Whiteway J. A., and Zent A. P. 2009. H_2O at the Phoenix landing site. *Science* 325:58–61. https://doi.org/10.1126/science.1172339.

Smoot J. P. and Lowenstein T. K. 1991. Depositional environments of non-marine evaporites. *Developments in Sedimentology* 50:189–347. https://doi.org/10.1016/S0070-4571(08)70261-9.

Spears D. A. 2012. The origin of tonsteins, an overview, and links with seatearths, fireclays and fragmental clay rocks. *International Journal of Coal Geology* 94:22–31. https://doi.org/10.1016/J.COAL.2011.09.008.

Spry J. A., Race M., Kminek G., Siegel B., and Conley C. 2018. Planetary protection knowledge gaps for future mars human missions: Stepwise progress in identifying and integrating science and technology needs. In *48th International Conference on Environmental Systems (abstract #ICES-2018-315)*. https://ttu-ir.tdl.org/ttu-ir/handle/2346/74252

Squyres S. W. and Knoll A. H. 2005. Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars. *Earth and Planetary Science Letters* 240:1–10. https://doi.org/10.1016/j.epsl.2005.09.038.

Squyres S. W., Grotzinger J. P., Arvidson R. E., Bell J. F., Calvin W., Christensen P. R., Clark B. C., Crisp J. A., Farrand W. H., Herkenhoff K. E., Johnson J. R., Klingelhöfer G., Knoll A. H., McLennan S. M., McSween H. Y. Jr, Morris R. V., Rice J. W. Jr, Rieder R., and Soderblom L. A. 2004. In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars. *Science* 306:1709–1714. https://doi.org/10.1126/science.1104559.

Squyres S. W., Arvidson R. E., Ruff S., Gellert R., Morris R. V., Ming D. W., Crumpler L., Farmer J. D., Des Marais D. J., Yen A., McLennan S. M., Calvin W., Bell J. F. III, Clark B. C., Wang A., McCoy T. J., Schmidt M. E., and De Souza P. A. 2008. Detection of silica-rich deposits on Mars. *Science* 320:1063–1067. https://doi.org/10.1126/science.1155429.

Stack K. M., Grotzinger J. P., Kah L. C., Schmidt M. E., Mangold N., Edgett K. S., Sumner D. Y., Siebach K. L., Nachon M., Lee R., Blaney D. L., Deflores L. P., Edgar L. A., Fairén A. G., Leshin L. A., Maurice S., Oehler D. Z., Rice M. S., and Wiens R. C. 2014. Diagenetic origin of nodules in the Sheepbed member, Yellowknife Bay formation, Gale crater, Mars. *Journal of Geophysical Research: Planets* 119:1637–1664. https://doi.org/10.1002/2014JE004617.

Stanley B. D., Hirschmann M. M., and Withers A. C. 2011. CO_2 solubility in Martian basalts and Martian atmospheric evolution. *Geochimica et Cosmochimica Acta* 75:5987–6003. https://doi.org/10.1016/J.GCA.2011.07.027.

Steele A., Goddard D. T., Stapleton D., Toporski J. K., Peters V., Bassinger V., Sharples G., Wynn-Williams D. D., and McKay D. S. 2000. Investigations into an unknown organism on the Martian meteorite Allan Hills 84001. *Meteoritics & Planetary Science* 35:237–241. http://www.ncbi.nlm.nih.gov/pubmed/11542972

Steele A., McCubbin F. M., Fries M., Kater L., Boctor N. Z., Fogel M. L., Conrad P. G., Glamoclija M., Spencer M., Morrow A. L., Hammond M. R., Zare R. N., Vicenzi E. P., Siljeström S., Bowden R., Herd C. D. K., Mysen B. O., Shirey S. B., Amundsen H. E. F., Treiman A. H., Bullock E. S., and Jull A. J. T. 2012. A reduced organic carbon component in Martian basalts. *Science* 337:212–215. https://doi.org/10.1126/science.1220715.

Steele A., McCubbin F. M., and Fries M. D. 2016. The provenance, formation, and implications of reduced carbon phases in Martian meteorites. *Meteoritics & Planetary Science* 51:2203–2225. https://doi.org/10.1111/maps.12670.

Steininger H., Goesmann F., and Goetz W. 2012. Influence of magnesium perchlorate on the pyrolysis of organic compounds in Mars analogue soils. *Planetary and Space Science* 71:9–17. https://doi.org/10.1016/J.PSS.2012.06.015.

Stephan T., Jessberger E. K., Heiss C. H., and Rost D. 2003. TOF-SIMS analysis of polycyclic aromatic hydrocarbons in Allan Hills 84001. *Meteoritics & Planetary Science* 38:109–116. https://doi.org/10.1111/j.1945-5100.2003.tb01049.x.

Stevens T. O. and McKinley J. P. 1995. Lithoautotrophic microbial ecosystems in deep basalt aquifers. *Science* 270:450–455. https://doi.org/10.1126/science.270.5235.450.

Stevenson D. J. 2001. Mars' core and magnetism. *Nature* 412:214–219. https://doi.org/10.1038/35084155.

Stoffregen R. E., Alpers C. N., and Jambor J. L. 2000. Alunite-Jarosite crystallography, thermodynamics, and geochronology. *Reviews in Mineralogy and Geochemistry* 40:453–479. https://doi.org/10.2138/rmg.2000.40.9.

Stolper E. M., Baker M. B., Newcombe M. E., Schmidt M. E., Treiman A. H., Cousin A., Dyar M. D., Fisk M. R., Gellert R., King P. L., Leshin L., Maurice S., McLennan S. M., Minitti M. E., Perrett G., Rowland S., Sautter V., Wiens R. C., and MSL Science Team. 2013. The petrochemistry of Jake_M: A martian mugearite. *Science* 341:1239463. https://doi.org/10.1126/science.1239463.

Summons R. E. and Hallmann C. 2014. Organic geochemical signatures of early life on Earth. In *Treatise on Geochemistry*. Amsterdam: Elsevier. pp. 33–46. https://doi.org/10.1016/b978-0-08-095975-7.01005-6

Summons R. E., Amend J. P., Bish D., Buick R., Cody G. D., Des Marais D. J., Dromart G., Eigenbrode J. L., Knoll A. H., and Sumner D. Y. 2011. Preservation of Martian organic and environmental records: Final report of the Mars Biosignature Working Group. *Astrobiology* 11:157–181. https://doi.org/10.1089/ast.2010.0506.

Summons R. E., Sessions A. L., Allwood A. C., Barton H. A., Beaty D. W., Blakkolb B., Canham J., Clark B. C., Dworkin J. P., Lin Y., Mathies R., Milkovich S. M., and Steele A. 2014. Planning considerations related to the organic contamination of Martian samples and implications for the Mars 2020 rover. *Astrobiology* 14:969–1027. https://doi.org/10.1089/ast.2014.1244.

Sutter B., McAdam A. C., Mahaffy P. R., Ming D. W., Edgett K. S., Rampe E. B., Eigenbrode J. L., Franz H. B., Freissinet C., Grotzinger J. P., Steele A., House C. H., Archer P. D., Malespin C. A., Navarro-González R., Stern J. C., Bell J. F., Calef F. J., Gellert R., Glavin D. P., Thompson L. M., and Yen A. S. 2017. Evolved gas analyses of sedimentary rocks and eolian sediment in Gale Crater, Mars: Results of the curiosity rover's sample analysis at Mars instrument from Yellowknife Bay to the Namib Dune. *Journal of Geophysical Research: Planets* 122:2574–2609. https://doi.org/10.1002/2016JE005225.

Swart P. K. 2015. The geochemistry of carbonate diagenesis: The past, present and future. *Sedimentology* 62:1233–1304. https://doi.org/10.1111/sed.12205.

Swindle T. D. 2002. Martian noble gases. *Reviews in Mineralogy and Geochemistry* 47:171–190. https://doi.org/10.2138/rmg.2002.47.6.

Swindle T., Caffee M., and Hohenberg C. 1986. Xenon and other noble gases in shergottites. *Geochimica et Cosmochimica Acta* 50:1001–1015. https://doi.org/10.1016/0016-7037(86)90381-9.

Swindle T. D., Treiman A. H., Lindstrom D. J., Burkland M. K., Cohen B. A., Grier J. A., Li B., and Olson E. K. 2000. Noble gases in iddingsite from the Lafayette meteorite: Evidence for liquid water on Mars in the last few hundred million years. *Meteoritics & Planetary Science* 35:107–115. https://doi.org/10.1111/j.1945-5100.2000.tb01978.x.

Swindle T. D., Thomas C., Mousis O., Lunine J. I., and Picaud S. 2009. Incorporation of argon, krypton and xenon into clathrates on Mars. *Icarus* 203:66–70. https://doi.org/10.1016/j.icarus.2009.04.004.

Symes S. J. K., Borg L. E., Shearer C. K., and Irving A. J. 2008. The age of the Martian meteorite Northwest Africa 1195 and the differentiation history of the shergottites. *Geochimica et Cosmochimica Acta* 72:1696–1710. https://doi.org/10.1016/J.GCA.2007.12.022.

Takai K., Nakamura K., Toki T., Tsunogai U., Miyazaki M., Miyazaki J., Hirayama H., Nakagawa S., Nunoura T., and Horikoshi K. 2008. Cell proliferation at 122 degrees C and isotopically heavy CH_4 production by a hyperthermophilic methanogen under high-pressure cultivation. *Proceedings of the National Academy of Sciences* 105:10,949–10,954. https://doi.org/10.1073/pnas.0712334105.

Tanaka K. L. 1997. Sedimentary history and mass flow structures of Chryse and Acidalia Planitiae, Mars. *Journal of Geophysical Research: Planets* 102:4131–4149. https://doi.org/10.1029/96JE02862.

Taylor F. W. 2011. Comparative planetology, climatology and biology of Venus, Earth and Mars. *Planetary and Space Science* 59:889–899. https://doi.org/10.1016/J.PSS.2010.11.009.

Taylor G. J. 2013. The bulk composition of Mars. *Chemie Der Erde—Geochemistry* 73:401–420. https://doi.org/10.1016/J.CHEMER.2013.09.006.

Taylor G. J., Boynton W., Brückner J., Wänke H., Dreibus G., Kerry K., Keller J., Reedy R., Evans L., Starr R., Squyres S., Karunatillake S., Gasnault O., Maurice S., d'Uston C., Englert P., Dohm J., Baker V., Hamara D., Janes D., Sprague A., Kim K., and Drake D. 2006. Bulk composition and early differentiation of Mars. *Journal of Geophysical Research* 112:E03S10. https://doi.org/10.1029/2005je002645

Taylor P. W. 2015. Impact of space flight on bacterial virulence and antibiotic susceptibility. *Infection and Drug Resistance* 8:249–262. https://doi.org/10.2147/IDR.S67275.

ten Kate I. L., Canham J. S., Conrad P. G., Errigo T., Katz I., and Mahaffy P. R. 2008. Mitigation of the impact of terrestrial contamination on organic measurements from the Mars Science Laboratory. *Astrobiology* 8:571–582. https://doi.org/10.1089/ast.2007.0160.

Tera F., Papanastassiou D. A., and Wasserburg G. J. 1974. Isotopic evidence for a terminal lunar cataclysm. *Earth and Planetary Science Letters* 22:1–21. https://doi.org/10.1016/0012-821X(74)90059-4.

Thollot P., Mangold N., Ansan V., Le Mouélic S., Milliken R. E., Bishop J. L., Weitz C. M., Roach L. H., Mustard J. F., and Murchie S. L. 2012. Most Mars minerals in a nutshell: Various alteration phases formed in a single environment in Noctis Labyrinthus. *Journal of Geophysical Research: Planets* 117. https://doi.org/10.1029/2011je004028

Thomas R. J., Potter-McIntyre S. L., and Hynek B. M. 2017. Large-scale fluid-deposited mineralization in Margaritifer Terra, Mars. *Geophysical Research Letters* 44:6579–6588. https://doi.org/10.1002/2017GL073388.

Thompson L. M. and Troeh F. R. 1978. *Soils and soil fertility*. New York: McGraw-Hill.

Thorpe M. T., Hurowitz J. H., and Dehouck E. 2017. A frigid terrestrial analog for the paleoclimate of Mars (abstract #2599). 48th Lunar and Planetary Science Conference. CD-ROM.

Thorseth I. H., Torsvik T., Torsvik V., Daae F. L., and Pedersen R. B. 2001. Diversity of life in ocean floor basalt. *Earth and Planetary Science Letters* 194:31–37. https://doi.org/10.1016/S0012-821X(01)00537-4.

Thorseth I. H., Pedersen R. B., and Christie D. M. 2003. Microbial alteration of 0–30-Ma seafloor and sub-seafloor basaltic glasses from the Australian Antarctic Discordance. *Earth and Planetary Science Letters* 215:237–247. https://doi.org/10.1016/S0012-821X(03)00427-8.

Tikoo S. M., Weiss B. P., Shuster D. L., Suavet C., Wang H., and Grove T. L. 2017. A two-billion-year history for the lunar dynamo. *Science Advances* 3:e1700207. https://doi.org/10.1126/sciadv.1700207.

Toporski J. and Steele A. 2007. Observations from a 4-year contamination study of a sample depth profile through Martian meteorite Nakhla. *Astrobiology* 7:389–401. https://doi.org/10.1089/ast.2006.0009.

Tornabene L. L., Osinski G. R., McEwen A. S., Wray J. J., Craig M. A., Sapers H. M., and Christensen P. R. 2013. An impact origin for hydrated silicates on Mars: A synthesis. *Journal of Geophysical Research: Planets* 118:994–1012. https://doi.org/10.1002/jgre.20082.

Tosca N. J., McLennan S. M., Lindsley D. H., and Schoonen M. A. A. 2004. Acid-sulfate weathering of synthetic Martian basalt: The acid fog model revisited. *Journal of Geophysical Research* 109:E05003. https://doi.org/10.1029/2003JE002218.

Tosca N. J., McLennan S. M., Clark B. C., Grotzinger J. P., Hurowitz J. A., Knoll A. H., Schröder C., and Squyres S. W. 2005. Geochemical modeling of evaporation processes on Mars: Insight from the sedimentary record at Meridiani Planum. *Earth and Planetary Science Letters* 240:122–148. https://doi.org/10.1016/J.EPSL.2005.09.042.

Tosca N. J., Knoll A. H., and McLennan S. M. 2008. Water activity and the challenge for life on early Mars. *Science* 320:1204–1207. https://doi.org/10.1126/science.1155432.

Tosca N. J., Ahmed I. A., Tutolo B. M., Ashpitel A., and Hurowitz J. A. in press. Magnetite authigenesis and the ancient Martian atmosphere. *Nature Geoscience*.

Trainer M. G., Franz H. B., Mahaffy P. R., Wong M. H., Atreya S. K., and McKay C. P. 2016. Update on the seasonal atmospheric composition measurements by the Sample Analysis at Mars instrument (abstract #1739). 47th Lunar and Planetary Science Conference. CD-ROM.

Treiman A. H. 2005. The nakhlite meteorites: Augite-rich igneous rocks from Mars. *Chemie Der Erde—Geochemistry* 65:203–270. https://doi.org/10.1016/J.CHEMER.2005.01.004.

Trembath-Reichert E., Morono Y., Ijiri A., Hoshino T., Dawson K. S., Inagaki F., and Orphan V. J. 2017. Methyl-compound use and slow growth characterize microbial life in 2-km-deep subseafloor coal and shale beds. *Proceedings of the National Academy of Sciences* 114: E9206–E9215. https://doi.org/10.1073/pnas.1707525114.

Tremblay M. M., Shuster D. L., and Balco G. 2014. Cosmogenic noble gas paleothermometry. *Earth and Planetary Science Letters* 400:195–205. https://doi.org/10.1016/J.EPSL.2014.05.040.

Trewin N. H., Fayers S. R., and Kelman R. 2003. Subaqueous silicification of the contents of small ponds in an Early Devonian hot-spring complex, Rhynie, Scotland. *Canadian Journal of Earth Sciences* 40:1697–1712. https://doi.org/10.1139/e03-065.

Tuff J., Wade J., and Wood B. J. 2013. Volcanism on Mars controlled by early oxidation of the upper mantle. *Nature* 498:342–345. https://doi.org/10.1038/nature12225.

Tyson R. V. 1995. *Sedimentary organic matter: Organic facies and palynofacies*. Dordrecht, the Netherlands: Springer. https://doi.org/10.1007/978-94-011-0739-6.

Ulrich M., Wagner D., Hauber E., De Vera J.-P., and Schirrmeister L. 2012. Habitable periglacial landscapes in Martian mid-latitudes. *Icarus* 219:345–357. https://doi.org/10.1016/J.ICARUS.2012.03.019.

Ushikubo T., Kita N. T., Cavosie A. J., Wilde S. A., Rudnick R. L., and Valley J. W. 2008. Lithium in Jack Hills zircons: Evidence for extensive weathering of Earth's earliest crust. *Earth and Planetary Science Letters* 272:666–676. https://doi.org/10.1016/J.EPSL.2008.05.032.

Usui T., Alexander C. M. O., Wang J., Simon J. I., and Jones J. H. 2015. Meteoritic evidence for a previously unrecognized hydrogen reservoir on Mars. *Earth and Planetary Science Letters* 410:140–151. https://doi.org/10.1016/J.EPSL.2014.11.022.

Vago J. L., Westall F., Pasteur Instrument Teams, Pasteur Landing Team, Coates A. J., Jaumann R., Korablev O., Ciarletti V., Mitrofanov I., Josset J.-L., De Sanctis M. C., Bibring J.-P., Rull F., Goesmann F., Steininger H., Goetz W., Brinckerhoff W., Szopa C., Raulin F., Westall F., Edwards H. G. M., Whyte L. G., Fairén A. G., Bibring J.-P., Bridges J., Hauber E., Ori G. G., Werner S., Loizeau D., Kuzmin R. O., Williams R. M. E., Flahaut J., Forget F., Vago J. L., Rodionov D., Korablev O., Svedhem H., Sefton-Nash E., Kminek G., Lorenzoni L., Joudrier L., Mikhailov V., Zashchirinskiy A., Alexashkin S., Calantropio F., Merlo A., Poulakis P., Witasse O., Bayle O., Bayón S., Meierhenrich U., Carter J., García-Ruiz J. M., Baglioni P., Haldemann A., Ball A. J., Debus A., Lindner R., Haessig F., Monteiro D., Trautner R., Voland C., Rebeyre P., Goulty D., Didot F., Durrant S., Zekri E., Koschny D., Toni A., Visentin G., Zwick M., and Van Winnendael M., Azkarate M., and Carreau C., ExoMars Project Team. 2017. Habitability on early Mars and the search for biosignatures with the ExoMars Rover. *Astrobiology* 17:471–510. https://doi.org/10.1089/ast.2016.1533.

Van Dover C. 2000. *The ecology of deep-sea hydrothermal vents*. Princeton, New Jersey: Princeton University Press. https://press.princeton.edu/titles/6880.html

Van Krevelen D. W. 1950. Graphical-statistical method for the study of structure and reaction processes of coal. *Fuel* 29:269–228.

Van Kooten E. M. M. E., Cavalcante L. L., Nagashima K., Kasama T., Balogh Z. I., Peeters Z., Hsiao S. S.-Y., Shang H., Lee D. C., Lee T., Krot A. N., and Bizzarro M. 2018. Isotope record of mineralogical changes in a spectrum of aqueously altered CM chondrites. *Geochimica et Cosmochimica Acta* 237:79–102. https://doi.org/10.1016/J.GCA.2018.06.021-&gt.

Vaniman D. T., Bish D. L., Ming D. W., Bristow T. F., Morris R. V., Blake D. F., Chipera S. J., Morrison S. M., Treiman A. H., Rampe E. B., Rice M., Achilles C. N., Grotzinger J. P., McLennan S. M., Williams J., Bell J. F. III, Newsom H. E., Downs R. T., Maurice S., Sarrazin P., Yen A. S., Morookian J. M., Farmer J. D., Stack K., Milliken R. E., Ehlmann B. L., Sumner D. Y., Berger G., Crisp J. A., Hurowitz J. A., Anderson R., Des Marais D. J., Stolper E. M., Edgett K. S., Gupta S., Spanovich N., and MSL Science Team. 2014. Mineralogy of a mudstone at Yellowknife Bay, Gale crater, Mars. *Science* 343:1243480. https://doi.org/10.1126/science.1243480.

Veizer J. and Mackenzie F. T. 2014. Evolution of sedimentary rocks. In *Treatise on Geochemistry*. Amsterdam: Elsevier. pp. 399–435. https://doi.org/10.1016/b978-0-08-095975-7.00715-4

Vermeesch P. 2004. How many grains are needed for a provenance study? *Earth and Planetary Science Letters* 224:441–451. https://doi.org/10.1016/J.EPSL.2004.05.037.

Vijendran S., Huesing J., Beyer F., and McSweeney A. 2018. Mars sample return—Earth return orbiter mission overview. In *2nd International Mars Sample Return Conference* (abstract #6124).

Villanueva G. L., Mumma M. J., Novak R. E., Kaufl H. U., Hartogh P., Encrenaz T., Tokunaga A., Khayat A., and Smith M. D. 2015. Strong water isotopic anomalies in the Martian atmosphere: Probing current and ancient reservoirs. *Science* 348:218–221. https://doi.org/10.1126/science.aaa3630.

Vreeland R. H., Rosenzweig W. D., and Powers D. W. 2000. Isolation of a 250 million-year-old halotolerant bacterium from a primary salt crystal. *Nature* 407:897–900. https://doi.org/10.1038/35038060.

Walter M. R. and Des Marais D. J. 1993. Preservation of biological information in thermal spring deposits: Developing a strategy for the search for fossil life on Mars. *Icarus* 101:129–143.

Walter M. R., Des Marais D. J., Farmer J. D., and Hinman N. W. 1996. Lithofacies and biofacies of mid-Paleozoic thermal spring deposits in the Drummond Basin, Queensland, Australia. *PALAIOS* 11:497. https://doi.org/10.2307/3515187.

Walton E. L., Kelley S. P., and Herd C. D. K. 2008. Isotopic and petrographic evidence for young Martian basalts. *Geochimica et Cosmochimica Acta* 72:5819–5837. https://doi.org/10.1016/J.GCA.2008.09.005.

Warren P. H. 1994. Lunar and Martian meteorite delivery services. *Icarus* 111:338–363. https://doi.org/10.1006/ICAR.1994.1149.

Warren P. H. 2011. Stable-isotopic anomalies and the accretionary assemblage of the Earth and Mars: A subordinate role for carbonaceous chondrites. *Earth and Planetary Science Letters* 311:93–100. https://doi.org/10.1016/J.EPSL.2011.08.047.

Watanabe Y., Martini J. E. J., and Ohmoto H. 2000. Geochemical evidence for terrestrial ecosystems 2.6 billion years ago. *Nature*, 408:574–578. https://doi.org/10.1038/35046052

Watanabe Y., Stewart B. W., and Ohmoto H. 2004. Organic- and carbonate-rich soil formation ~2.6 billion years ago at Schagen, East Transvaal district, South Africa.

Geochimica et Cosmochimica Acta 68:2129–2151. https://doi.org/10.1016/j.gca.2003.10.036

Watkins J. A., Grotzinger J. P., Stein N., Banham S. G., Gupta S., Rubin D. M., Stack K. M., and Edgett K. S. 2016. Paleotopography of erosional unconformity, base of Stimson formation, Gale crater, Mars (abstract #2939). 47th Lunar and Planetary Science Conference. CD-ROM.

Webster C. R., Mahaffy P. R., Flesch G. J., Niles P. B., Jones J. H., Leshin L. A., Atreya S. K., Stern J. C., Christensen L. E., Owen T., Franz H., Pepin R. O., Steele A., MSL Science Team, Achilles C., Agard C., Alves Verdasca J. A., Anderson R., Anderson R., Archer D., Armiens-Aparicio C., Arvidson R., Atlaskin E., Aubrey A., Baker B., Baker M., Balic-Zunic T., Baratoux D., Baroukh J., Barraclough B., Bean K., Beegle L., Behar A., Bell J., Bender S., Benna M., Bentz J., Berger G., Berger J., Berman D., Bish D., Blake D. F., Blanco Avalos J. J., Blaney D., Blank J., Blau H., Bleacher L., Boehm E., Botta O., Böttcher S., Boucher T., Bower H., Boyd N., Boynton B., Breves E., Bridges J., Bridges N., Brinckerhoff W., Brinza D., Bristow T., Brunet C., Brunner A., Brunner W., Buch A., Bullock M., Burmeister S., Cabane M., Calef F., Cameron J., Campbell J., Cantor B., Caplinger M., Caride Rodríguez J., Carmosino M., Carrasco Blázquez I., Charpentier A., Chipera S., Choi D., Clark B., Clegg S., Cleghorn T., Cloutis E., Cody G., Coll P., Conrad P., Coscia D., Cousin A., Cremers D., Crisp J., Cros A., Cucinotta F., d'Uston C., Davis S., Day M., De la Torre Juarez M., De Flores L., De Lapp D., De Marines J., Des Marais D., Dietrich W., Dingler R., Donny C., Downs B., Drake D., Dromart G., Dupont A., Duston B., Dworkin J., Dyar M. D., Edgar L., Edgett K., Edwards C., Edwards L., Ehlmann B., Ehresmann B., Eigenbrode J., Elliott B., Elliott H., Ewing R., Fabre C., Fairén A., Farley K., Farmer J., Fassett C., Favot L., Fay D., Fedosov F., Feldman J., Feldman S., Fisk M., Fitzgibbon M., Floyd M., Flückiger L., Forni O., Fraeman A., Francis R., François P., Freissinet C., French K. L., Frydenvang J., Gaboriaud A., Gailhanou M., Garvin J., Gasnault O., Geffroy C., Gellert R., Genzer M., Glavin D., Godber A., Goesmann F., Goetz W., Golovin D., Gómez Gómez F., Gómez-Elvira J., Gondet B., Gordon S., Gorevan S., Grant J., Griffes J., Grinspoon D., Grotzinger J., Guillemot P., Guo J., Gupta S., Guzewich S., Haberle R., Halleaux D., Hallet B., Hamilton V., Hardgrove C., Harker D., Harpold D., Harri A. M., Harshman K., Hassler D., Haukka H., Hayes A., Herkenhoff K., Herrera P., Hettrich S., Heydari E., Hipkin V., Hoehler T., Hollingsworth J., Hudgins J., Huntress W., Hurowitz J., Hviid S., Iagnemma K., Indyk S., Israël G., Jackson R., Jacob S., Jakosky B., Jensen E., Jensen J. K., Johnson J., Johnson M., Johnstone S., Jones A., Joseph J., Jun I., Kah L., Kahanpää H., Kahre M., Karpushkina N., Kasprzak W., Kauhanen J., Keely L., Kemppinen O., Keymeulen D., Kim M. H., Kinch K., King P., Kirkland L., Kocurek G., Koefoed A., Köhler J., Kortmann O., Kozyrev A., Krezoski J., Krysak D., Kuzmin R., Lacour J. L., Lafaille V., Langevin Y., Lanza N., Lasue J., Le Mouélic S., Lee E. M., Lee Q. M., Lees D., Lefavor M., Lemmon M., Lepinette Malvitte A., Léveillé R., Lewin-Carpintier É., Lewis K., Li S., Lipkaman L., Little C., Litvak M., Lorigny E., Lugmair G., Lundberg A., Lyness E., Madsen M., Maki J., Malakhov A., Malespin C., Malin M., Mangold N., Manhes G., Manning H., Marchand G., Marín Jiménez M., Martín García C., Martin D., Martin M., Martínez-Frías J., Martín-Soler J., Martín-Torres F. J., Mauchien P., Maurice S., McAdam A., McCartney E., McConnochie T., McCullough E., McEwan I., McKay C., McLennan S., McNair S., Melikechi N., Meslin P. Y., Meyer M., Mezzacappa A., Miller H., Miller K., Milliken R., Ming D., Minitti M., Mischna M., Mitrofanov I., Moersch J., Mokrousov M., Molina Jurado A., Moores J., Mora-Sotomayor L., Morookian J. M., Morris R., Morrison S., Mueller-Mellin R., Muller J. P., Muñoz Caro G., Nachon M., Navarro López S., Navarro-González R., Nealson K., Nefian A., Nelson T., Newcombe M., Newman C., Newsom H., Nikiforov S., Nixon B., Noe Dobrea E., Nolan T., Oehler D., Ollila A., Olson T., De Pablo Hernández M. Á., Paillet A., Pallier E., Palucis M., Parker T., Parot Y., Patel K., Paton M., Paulsen G., Pavlov A., Pavri B., Peinado-González V., Peret L., Perez R., Perrett G., Peterson J., Pilorget C., Pinet P., Pla-García J., Plante I., Poitrasson F., Polkko J., Popa R., Posiolova L., Posner A., Pradler I., Prats B., Prokhorov V., Purdy S. W., Raaen E., Radziemski L., Rafkin S., Ramos M., Rampe E., Raulin F., Ravine M., Reitz G., Rennó N., Rice M., Richardson M., Robert F., Robertson K., Rodriguez Manfredi J. A., Romeral-Planelló J. J., Rowland S., Rubin D., Saccoccio M., Salamon A., Sandoval J., Sanin A., Sans Fuentes S. A., Saper L., Sarrazin P., Sautter V., Savijärvi H., Schieber J., Schmidt M., Schmidt W., Scholes D., Schoppers M., Schröder S., Schwenzer S., Sebastian Martinez E., Sengstacken A., Shterts R., Siebach K., Siili T., Simmonds J., Sirven J. B., Slavney S., Sletten R., Smith M., Sobrón Sánchez P., Spanovich N., Spray J., Squyres S., Stack K., Stalport F., Stein T., Stewart N., Stipp S. L., Stoiber K., Stolper E., Sucharski B., Sullivan R., Summons R., Sumner D., Sun V., Supulver K., Sutter B., Szopa C., Tan F., Tate C., Teinturier S., ten Kate I., Thomas P., Thompson L., Tokar R., Toplis M., Torres Redondo J., Trainer M., Treiman A., Tretyakov V., Urqui-O'Callaghan R., Van Beek J., Van Beek T., Van Bommel S., Vaniman D., Varenikov A., Vasavada A., Vasconcelos P., Vicenzi E., Vostrukhin A., Voytek M., Wadhwa M., Ward J., Weigle E., Wellington D., Westall F., Wiens R. C., Wilhelm M. B., Williams A., Williams J., Williams R., Williams R. B., Wilson M., Wimmer-Schweingruber R., Wolff M., Wong M., Wray J., Wu M., Yana C., Yen A., Yingst A., Zeitlin C., and Zimdar R., and Zorzano Mier M.-P. 2013. Isotope ratios of H, C, and O in CO_2 and H_2O of the Martian atmosphere. *Science* 341:260–263. https://doi.org/10.1126/science.1237961.

Webster C. R., Mahaffy P. R., Atreya S. K., Flesch G. J., Mischna M. A., Meslin P.-Y., Farley K. A., Conrad P. G., Christensen L. E., Pavlov A. A., Martín-Torres J., Zorzano M. P., McConnochie T. H., Owen T., Eigenbrode J. L., Glavin D. P., Steele A., Malespin C. A., Archer P. D. Jr., Sutter B., Coll P., Freissinet C., McKay C. P., Moores J. E., Schwenzer S. P., Bridges J. C., Navarro-Gonzalez R., Gellert R., Lemmon M. T., and MSL Science Team. 2015. Mars atmosphere. Mars methane detection and variability at Gale crater. *Science* 347:415–417. https://doi.org/10.1126/science.1261713

Webster C. R., Mahaffy P. R., Atreya S. K., Moores J. E., Flesch G. J., Malespin C., McKay C. P., Martinez G., Smith C. L., Martin-Torres J., Gomez-Elvira J., Zorzano

M. P., Wong M. H., Trainer M. G., Steele A., Archer D. Jr, Sutter B., Coll P. J., Freissinet C., Meslin P. Y., Gough R. V., House C. H., Pavlov A., Eigenbrode J. L., Glavin D. P., Pearson J. C., Keymeulen D., Christensen L. E., Schwenzer S. P., Navarro-Gonzalez R., Pla-García J., Rafkin S. C. R., Vicente-Retortillo Á., Kahanpää H., Viudez-Moreiras D., Smith M. D., Harri A. M., Genzer M., Hassler D. M., Lemmon M., Crisp J., Sander S. P., Zurek R. W., and Vasavada A. R. 2018. Background levels of methane in Mars' atmosphere show strong seasonal variations. *Science* 360:1093–1096. https://doi.org/10.1126/science.aaq0131.

Weiss B. P., Kim S. S., Kirschvink J. L., Kopp R. E., Sankaran M., Kobayashi A., and Komeili A. 2004. Magnetic tests for magnetosome chains in Martian meteorite ALH84001. *Proceedings of the National Academy of Sciences* 101:8281–8284. https://doi.org/10.1073/pnas.0402292101.

Weiss B. P., Fong L. E., Vali H., Lima E. A., and Baudenbacher F. J. 2008. Paleointensity of the ancient Martian magnetic field. *Geophysical Research Letters* 35: L23207. https://doi.org/10.1029/2008GL035585.

Weiss B. P., Returned Sample Science Board (RSSB): Beaty D. W., McSween H. Y., Carrier B. L., Czaja A. D., Goreva Y., Hausrath E., Herd C. D. K., Humayun M., McCubbin F. M., McLennan S. M., Pratt L. M., and Sephton M. A., and Steele A. 2018. Paleomagnetic studies of returned samples from Mars. In *2nd International Mars Sample Return Conference* (abstract #6099).

Weltje G. J. and von Eynatten H. 2004. Quantitative provenance analysis of sediments: Review and outlook. *Sedimentary Geology* 171:1–11. https://doi.org/10.1016/J.SEDGEO.2004.05.007.

Werner S. C. 2009. The global Martian volcanic evolutionary history. *Icarus* 201:44–68. https://doi.org/10.1016/J.ICARUS.2008.12.019.

Werner S. C., Ody A., and Poulet F. 2014. The source crater of Martian shergottite meteorites. *Science* 343:1343–1346. https://doi.org/10.1126/science.1247282.

West A. J., Galy A., and Bickle M. 2005. Tectonic and climatic controls on silicate weathering. *Earth and Planetary Science Letters* 235:211–228. https://doi.org/10.1016/J.EPSL.2005.03.020.

Westall F., Cavalazzi B., Lemelle L., Marrocchi Y., Rouzaud J.-N., Simionovici A., Salomé M., Mostefaoui S., Andreazza C., Foucher F., Toporski J., Jauss A., Thiel V., Southam G., MacLean L., Wirick S., Hofmann A., Meibom A., and Défarge C. 2011a. Implications of in situ calcification for photosynthesis in a ~ 3.3 Ga-old microbial biofilm from the Barberton greenstone belt, South Africa. *Earth and Planetary Science Letters* 310: 468–479. https://doi.org/10.1016/j.epsl.2011.08.029

Westall F., Foucher F., Cavalazzi B., De Vries S. T., Nijman W., Pearson V., Watson J., Verchovsky A., Wright I., Rouzaud J.-N., Marchesini D., and Anne S. 2011b. Volcaniclastic habitats for early life on Earth and Mars: A case study from ~3.5 Ga-old rocks from the Pilbara, Australia. *Planetary and Space Science* 59:1093–1106. https://doi.org/10.1016/j.pss.2010.09.006

Westall F., Foucher F., Bost N., Bertrand M., Loizeau D., Vago J. L., Kminek G., Gaboyer F., Campbell K. A., Bréhéret J.-G., Gautret P., and Cockell C. S. 2015a. Biosignatures on Mars: What, where, and how? Implications for the search for Martian life. *Astrobiology* 15:998–1029. https://doi.org/10.1089/ast.2015.1374.

Westall F., Campbell K. A., Bréhéret J. G., Foucher F., Gautret P., Hubert A., Sorieul S., Grassineau N, and Guido D. M. 2015b. Archean (3.33 Ga) microbe-sediment systems were diverse and flourished in a hydrothermal context. *Geology*, 43:615–618. https://doi.org/10.1130/g36646.1

Westall F., Hickman-Lewis K., Hinman N., Gautret P., Campbell K. A., Bréhéret J. G., Foucher F., Hubert A., Sorieul S., Dass A. V., Kee T. P., Georgelin T., and Brack A. 2018. A hydrothermal-sedimentary context for the origin of life. *Astrobiology* 18:259–293. https://doi.org/10.1089/ast.2017.1680.

Weyrich L. S., Llamas B., and Cooper A. 2014. Reply to Santiago-Rodriguez *et al.*: Was *luxS* really isolated from 25- to 40-million-year-old bacteria? *FEMS Microbiology Letters* 353:85–86. https://doi.org/10.1111/1574-6968.12415

Whalley W. B. 1978. Scanning electron microscopy in the study of sediments. In *Geo Abstracts*. Norwich, England. pp. 181–191. https://trove.nla.gov.au/work/9794354?q&versionId=11370938

Wheeler R. M. 2004. Horticulture for Mars. *Proceedings XXVI International Horticultural Congress – Colloquia Presentations*. Acta Hort. 642, ISHS 2004.

Whitman W. B., Coleman D. C., Wiebe W. J., Smith D. C., and D'Hondt S. 1998. Prokaryotes: The unseen majority. *Proceedings of the National Academy of Sciences* 95:6578–6583. https://doi.org/10.1073/pnas.95.12.6578.

Wiederhold J. G. 2015. Metal stable isotope signatures as tracers in environmental geochemistry. *Environmental Science & Technology* 49:2606–2624. https://doi.org/10.1021/es504683e.

Wiens R. C. 1988. Noble gases released by vacuum crushing of EETA 79001 glass. *Earth and Planetary Science Letters* 91:55–65. https://doi.org/10.1016/0012-821X(88)90150-1.

Williams R. M. E., Grotzinger J. P., Dietrich W. E., Gupta S., Sumner D. Y., Wiens R. C., Mangold N., Malin M. C., Edgett K. S., Maurice S., Forni O., Gasnault O., Ollila A., Newsom H. E., Dromart G., Palucis M. C., Yingst R. A., Anderson R. B., Herkenhoff K. E., Le Mouélic S., Goetz W., Madsen M. B., Koefoed A., Jensen J. K., Bridges J. C., Schwenzer S. P., Lewis K. W., Stack K. M., Rubin D., Kah L. C., Bell J. F. 3rd, Farmer J. D., Sullivan R., Van Beek T., Blaney D. L., Pariser O., Deen R. G., and MSL Science Team. 2013. Martian fluvial conglomerates at Gale crater. *Science* 340:1068–1072. https://doi.org/10.1126/science.1237317.

Williford K. H., Ushikubo T., Lepot K., Kitajima K., Hallmann C., Spicuzza M. J., Kozdon R., Eigenbrode J. L., Summons R. E., and Valley J. W. 2016. Carbon and sulfur isotopic signatures of ancient life and environment at the microbial scale: Neoarchean shales and carbonates. *Geobiology* 14:105–128. https://doi.org/10.1111/gbi.12163.

Winterhalter D., Levine J. S., Kerschmann R., Beaty D. W., Carrier B. L., and Ashley J. W. 2018. The potential impact of Mars' atmospheric dust on future human exploration of the red planet: Mars sample return considerations. In *2nd International Mars Sample Return Conference* (abstract #6105).

Woese C. R. and Fox G. E. 1977. Phylogenetic structure of the prokaryotic domain: The primary kingdoms.

Proceedings of the National Academy of Sciences 74:5088–5090. https://doi.org/10.1073/PNAS.74.11.5088.
Wong M. H., Atreya S. K., Mahaffy P. N., Franz H. B., Malespin C., Trainer M. G., Stern J. C., Conrad P. G., Manning H. L. K., Pepin R. O., Becker R. H., McKay C. P., Owen T. C., Navarro-González R., Jones J. H., Jakosky B. M., and Steele A. 2013. Isotopes of nitrogen on Mars: Atmospheric measurements by Curiosity's mass spectrometer. *Geophysical Research Letters* 40:6033–6037. https://doi.org/10.1002/2013GL057840.
Wray J. J., Murchie S. L., Bishop J. L., Ehlmann B. L., Milliken R. E., Wilhelm M. B., Seelos K. D., and Chojnacki M. 2016. Orbital evidence for more widespread carbonate-bearing rocks on Mars. *Journal of Geophysical Research: Planets* 121:652–677. https://doi.org/10.1002/2015JE004972.
Yen A. S., Morris R. V., Clark B. C., Gellert R., Knudson A. T., Squyres S., Mittlefehldt D. W., Ming D. W., Arvidson R., McCoy T., Schmidt M., Hurowitz J., Li R., and Johnson J. R. 2008. Hydrothermal processes at Gusev Crater: An evaluation of Paso Robles class soils. *Journal of Geophysical Research* 113:E06S10. https://doi.org/10.1029/2007je002978
Yoder C. F., Konopliv A. S., Yuan D. N., Standish E. M., and Folkner W. M. 2003. Fluid core size of Mars from detection of the solar tide. *Science* 300:299–303. https://doi.org/10.1126/science.1079645.
Zerkle A. L., House C. H., and Brantley S. L. 2005. Biogeochemical signatures through time as inferred from whole microbial genomes. *American Journal of Science* 305:467–502. https://doi.org/10.2475/ajs.305.6-8.467.
Zurbuchen T. 2017. NASA Mars Exploration Program. In *Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences*. http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_181241.pdf

APPENDIX 1: IMOST TERMS OF REFERENCE

HISTORICAL NOTE: This Terms of Reference document was prepared at the time NASA, ESA, and IMEWG were in the early stages of planning the The 2nd International Mars Sample Return Conference, which was subsequently held April 25–27, 2018 in Berlin. One of the purposes of the study described below was to generate sample-related information as input to that conference. All of the documentation of the Berlin conference is archived at the following web site:
https://atpi.eventsair.com/QuickEventWebsitePortal/2nd-international-conference-on-mars-sample-return/home.
The committee that carried out this Terms of Reference adopted the name International MSR Objectives/Samples Team (iMOST), and the members of this committee are listed below in Appendix 2.

Introduction

The analysis of samples returned from Mars is of interest to the international Mars exploration community. IMEWG (International Mars Exploration Working Group) is currently exploring options to involve the international community in the conduct of sample collection and the analysis of the returned samples. The sample-caching rover is an essential component of a Mars Sample Return campaign, so the existence of the Mars 2020 mission constitutes a critical opportunity to make progress on MSR. The Mars 2020 samples, when returned, would provide the basis for performing a variety of Earth-based experiments including ones related to the search for signs of life.

In mid-2017, NASA opened the possibility of a MSR campaign in the next decade, available to potential participation of the international space community. The possibilities presented are currently being evaluated by IMEWG. As part of this evaluation, IMEWG is chartering the International MSR Objectives/Samples Team (iMOST) to characterize the kinds of samples that would be needed to achieve the MSR scientific objectives, and the types of measurements that would need to be made on those samples once returned to Earth.

IMEWG is currently planning a major conference on Mars Sample Return in April 2018, and it is expected that this charter group will deliver a draft report at the meeting. The April conference will be sponsored primarily by ESA and on the 10th anniversary year of IMEWG's first MSR conference, which was held in 2008.

There are two main reasons why an updated analysis of the science potential of MSR is now appropriate:

1. The last major analysis of the specific scientific objectives of MSR, and how they translate to sample types and sample quantities was the MEPAG E2E-iSAG (End-to-End International Science Analysis Group) analysis carried out in 2010-11 (and published in early 2012). Since then, there have been advances on different fronts that may change our perception of the scientific priorities for MSR:
   - The number of Mars meteorites in our collections on Earth has now grown to over 100 (this number was 55 in 2011), and includes one brecciated sample that has a different age from all the other Martian meteorites, and is thus presumably representative of a different region of Mars.
   - The Curiosity rover landed on Mars (Aug. 2012), and has operated successfully for more than 5 years. Its suite of instruments has recognized a different chemistry for the Martian surface with its identification of abundant perchlorates. In addition, scientific output from the wealth of data returned by orbiter missions since 2011, such as

NASA's Mars Reconnaissance Orbiter and Mars Odyssey, as well as ESA's Mars Express, has been fundamentally important in shaping and improving our understanding of the Martian surface.

- Research on terrestrial analogs, especially in the general field of astrobiology, has blossomed. We have a better understanding of the relationship of life to its environment, and of changes with time.
- There have been substantial improvements in our ability to handle and analyze very small samples. A highly visible example is the work that has been done on the Hayabusa samples (JAXA), and the associated instrumentation developments around the world.

2. As part of the planning for the investigation of the samples after they arrive on Earth, we need a systematic analysis of which measurements would need to be made on the samples in order to achieve the diverse scientific objectives of MSR. This information can be used to derive an instrument list and the logical progression of analyses. This is key input into planning for the sample receiving facility, for one or more curation facilities, and for certain key operational decisions.

Assumptions

We request that this study be constrained by the following assumptions:

1. The starting point for evaluating MSR science objectives will be the MEPAG E2E-iSAG (2011) analysis and the subsequent derivative work by the Returned Sample Science Board (RSSB), soon to be published.
2. In order to be specific, samples to be considered for this study will be limited to rock and regolith samples able to be collected and cached by the Mars 2020 rover, and an atmospheric gas sample that could be collected by the retrieval mission. Rock and regolith investigations will be limited to those that can be achieved using samples of the size and quality that can be collected using the Mars 2020 sampling system.

Requested Deliverables

1. A reviewable draft report, in both text- and PPT-format is requested by April 1, 2018. It is assumed that one or more presentations on this material will be given at the April MSR Conference, and that the committee will consider any feedback received as they prepare the final version of the report. This report will contain:
   a) An updated, consensus list of the potential science objectives of MSR, identifying those achievable based on the above assumptions (recognizing that sample-related science objectives are site-dependent, yet most of the objectives can be met at any one landing site). However, the first sample return campaign would be implemented, and whichever objectives are achieved, the remaining objectives may thereby form the basis for future sample returns.
   b) A list of options and priorities for contingency samples that could increase or secure science return.
   c) An analysis of the kinds of samples required/desired to achieve the various scientific objectives.
   d) An evaluation of the specific Earth-based measurements that would need to be made on candidate samples to achieve the objectives.
   e) An analysis of the possible design of sample suites that may enhance our ability to achieve the scientific objectives of MSR, and that could be considered by the M-2020 science team as they plan sample collection traverses.
2. A final version of the report is requested by July 1, 2018 (2 months after the end of the MSR Conference), incorporating feedback from the Conference. It is hoped that the final version of the report will be submitted for publication in one of the professional journals. This report may not contain any material that is proprietary or sensitive—we need to be able to use it in open forum, such as the COSPAR Assembly in July 2018.
3. If time permits, a reference table of the instruments and associated sample preparation equipment necessary to achieve the scientific objectives of MSR. The list may, in part, be dependent on the types of samples delivered to Earth, and in part be contingent on advances in analytical techniques, thus cannot be more than a working draft, but would provide a useful framework for planning the post-receipt period.

It is possible that an extension into follow-up activities may be requested after the April MSR Conference.

Team, logistics

- Steering of the science team's work shall be performed by a leadership team, which shall include NASA and ESA representatives and the co-chairs of the science team.
- It is expected that the science team will be configured with appropriate intellectual, international, organizational, and gender diversity.
- The logistics for the team will be managed by the Mars Program Office, at JPL, and may be supported as needed by participating organizations.

- Other than planning for a single face-to-face meeting of the leadership team, it is expected that all of the team's work will be carried out using e-mail and teleconference processes.

Michael Meyer, David Parker, and Jim Watzin, on behalf of IMEWG

November 9, 2017

APPENDIX 2: IMOST TEAM ROSTER AND AFFILIATIONS

Name	Institution	Nation represented
Co-Chairs:		
Beaty, David	Jet Propulsion Laboratory/ California Institute of Technology	US
Grady, Monica	Open University	UK
McSween, Hap	Univ. of Tennessee	US
Sefton-Nash, Elliot	ESTEC	ESA
Facilitation:		
Carrier, Brandi	Jet Propulsion Laboratory/ California Institute of Technology	US
Team Members:		
Altieri, Francesca	IAPS—INAF	Italy
Amelin, Yuri	Australian National University	Australia
Ammannito, Eleonora	ASI	Italy
Anand, Mahesh	Open University	UK
Benning, Liane	German Research Center for Geosciences	Germany
Bishop, Janice	SETI Institute	US
Borg, Lars	Lawrence Livermore Lab	US
Boucher, Dale	Deltion Innovations	Canada
Brucato, John R.	OA-Arcetri	Italy
Busemann, Henner	ETH Zurich	Switzerland
Campbell, Kathy	University of Auckland	New Zealand
Carrier, Brandi	Jet Propulsion Laboratory/ California Institute of Technology	US
Czaja, Andy	Univ. of Cincinnati	US
Debaille, Vinciane	Universite Libre de Bruxelles	Belgium
Des Marais, Dave	NASA Ames Research Center	US
Dixon, Mike	University of Guelph	Canada

Appendix. *Continued.* iMOST Team Roster and Affiliation

Name	Institution	Nation represented
Ehlmann, Bethany	California Institute of Technology	US
Farmer, Jack	Arizona State University	US
Fernandez-Remolar, David	Luleå University of Technology	Sweden
Filiberto, Justin	Southern Illinois University	US
Fogarty, Jennifer	NASA Johnson Space Center	US
Glavin, Danny	NASA Goddard Space Flight Center	US
Goreva, Yulia	Jet Propulsion Laboratory/ California Institute of Technology	US
Hallis, Lydia	Glasgow University	UK
Harrington, Andrea	NASA Johnson Space Center	US
Hausrath, Libby	Univ. of Nevada, Las Vegas	US
Herd, Chris	Univ. of Alberta	Canada
Horgan, Briony	Purdue University	US
Humayun, Munir	Florida State Univ	US
Kleine, Thorsten	University of Muenster	Germany
Kleinhenz, Julie	NASA Glenn Research Center	US
Mangold, Nicolas	University of Nantes-LPG	France
Mackelprang, Rachel	Cal State-Northridge	US
Mayhew, Lisa	Univ. Colorado	US
McCubbin, Francis	NASA Johnson Space Center	US
McCoy, Torin	NASA Johnson Space Center	US
McLennan, Scott	Stony Brook Univ.	US
Moser, Desmond	Western University	Canada
Moynier, Frederic	Paris Institute of Earth Physics	France
Mustard, Jack	Brown University	US
Niles, Paul	NASA Johnson Space Center	US
Ori, Gian G.	Int. Research Sch. of Planet. Sci. Universita d'Annunzio	Italy
Raulin, Francois	University of Paris (UPEC)	France
Rettberg, Petra	German Aerospace Center (DLR)	Germany
Rucker, Michelle	NASA Johnson Space Center	US

Appendix. *Continued.* iMOST Team Roster and Affiliation

Name	Institution	Nation represented
Schmitz, Nicole	German Aerospace Center (DLR)	Germany
Schwenzer, Susanne	Open University	UK
Sephton, Mark	Imperial College	UK
Shaheen, Robina	University of California San Diego	US
Sharp, Zachary	University of New Mexico	US
Shuster, David	University of California Berkeley	US
Siljestrom, Sandra	Research Institutes of Sweden, Stockholm	Sweden
Smith, Caroline	Natural History Museum, London	UK
Spry, Andy	SETI Institute	US
Steele, Andrew	Carnegie Institution of Washington	US
Swindle, Tim	Universitiy of Arizona	US
ten Kate, Inge Loes	Utrecht University	NL
Tosca, Nick	Oxford University	UK
Usui, Tomo	Tokyo Institue of Technology	Japan
Van	Kranendonk, Martin	UNSW Sydney
Australia		
Wadhwa, Mini	Arizona State University	US
Weiss, Ben	Massachusetts Institute of Technology	US
Werner, Stephanie	University of Oslo	Norway
Westall, Frances	CNRS-Orleans	France
Wheeler, Ray	NASA Kennedy Space Center	US
Zipfel, Jutta	Senckenberg Research Inst, Frankfurt	Germany
Zorzano, Maria Paz	Centro de Astrobiologia	Spain

APPENDIX 3: EXPECTED SIZE AND QUALITY OF THE SAMPLES TO BE COLLECTED BY MARS 2020

Over approximately the last 4 years, sample quality standards have been established by several different methods to ensure that the MSR samples will be able to address the planned scientific objectives, within the necessary constraints of mission design and cost (Beaty et al. 2014; Liu et al. 2014a, 2014b; Carrier et al. 2017b). Some of these standards were formulated for the M-2020 Project by the Returned Sample Science

Table A3.1. Campaign-level science requirements for Mars samples.

Sample Quality Parameter	Recommended Requirement
Biologic contamination	<1 viable terrestrial organism per tube
Organic contamination	Tier 1 compounds <1 ppb Tier 2 compounds <10 ppb TOC <40 ppb
Inorganic contamination	Zr, Nb, Ta, La, Ce, Eu, Gd, Li, B, Cs, Sc, Mn, Y, Mg, Zn, Ni, Co, Cl, Br, P, S <1% K, Rb, Sr, Sm, Nd, U, Th, Re, Os, Lu, Hf, W <0.1% Pb <2 ng/g
Magnetics	Exposure to <0.5 mT Shock pressure <0.1GPa Orientation to half-cone uncertainty of <5°
Fracturing	Size distribution in a single core of <20% by mass in pieces ≤2 mm, and >70% by mass in pieces with largest dimension >10 mm
Internal movement	Minimize by preloading tubes compatible with X-ray CT imaging of core before removal
Temperature	<60 °C required, <40 °C desired
Cross contamination	<150 mg per samples tube
Sealing	<1% water, translated to He leak rate for 20 years
Radiation	<100 krad over 20 years

Board (RSSB), a group chartered in mid-2015 by NASA to represent the sample scientific community who will study the returned samples, and others were formulated by predecessors of the RSSB (and the RSSB never found a reason to modify the specifications) (Beaty et al. 2014; RSSB 2016a, 2016b, 2018b, 2018c). Table A.3.1 summarizes the full set of sample quality requirements compiled by RSSB (2018b), and which are described below.

Earth-sourced contamination: Minimizing Earth-sourced contamination is critically important for geochemistry, isotope geochronology, and astrobiology investigations. Mars-sourced contaminants will be monitored by witness blanks.

Organic compounds: The limits for Earth-sourced organic carbon in/on the samples originated from a nearly year-long study by a science/Planetary Protection team (OCP) carried out in 2014 (2). Their final recommendation was organized into three components: <1 ppb Tier 1 compounds (organic compounds that would be deliberately evaluated in returned samples as input to life-related interpretations), <10 ppb other C-compounds (everything that is not on the Tier 1 list), and <40 ppb total organic carbon (TOC).

Inorganic elements: The key input for this originated at the "Workshop on MSR Sample Quality," March 16, 2014 (a pre-LPSC workshop), in part aided by a pre-RSSB focus group. It was recognized that for most kinds of elemental geochemistry studies, the data do not matter beyond two significant figures. Thus, for the following elements: Zr, Nb, Ta, La, Ce, Eu, Gd, Li, B, Cs, Sc, Mn, Y, Mg, Zn, Ni, Co, Cl, Br, P, and S, agreement was reached to limit Earth-sourced inorganic contamination to ≤1% of the concentration in Martian meteorites (and Tissint was later chosen as the reference). However, this accuracy is not sufficient for geochronology studies, such that for the primary parent-daughter pairs (K, Rb, Sr, Sm, Nd, U, Th, Re, Os, Lu, Hf, and W) a constraint of ≤ 0.1% was adopted (it was subsequently recognized that W may be subject to unavoidable contamination from the WC cutters in the drill bits). Several elements required to build the spacecraft (e.g., Ti, Al, Fe) were left unconstrained. Pb contamination was identified as being of interest at a very low level (~0.1% of the concentration in Martian meteorites), to allow for U-Th-Pb geochronology, although this is a notoriously difficult contaminant to deal with on Earth. Initial element lists developed above were refined in a 2014 GSA poster (Liu et al. 2014a).

Magnetics: A pre-RSSB magnetics focus group, led by B. Weiss in 2014, conducted a study to assess the requirements for magnetics measurements on one or more returned samples. These include limitations on exposure to a spacecraft magnetic fields (<0.5 mT), shock intensity during launch and landing (<0.1 GPa), and accuracy to which orientation should be determined with respect to their pre-sampling positions on the Martian surface based on a surface features (to within 5°). Furthermore, to ensure that paleomagnetic directional measurements can be oriented with respect to absolute Martian geographic coordinates at the time the magnetization was acquired by the samples, their parent rocks should be in-place bedrock or at least blocks with paleohorizontal indicators (i.e., bedding planes, flow-top features, vesicularity or crystal size gradients, and/or stratified grain size sorting) (RSSB 2016a, 2016b; Weiss et al. 2018).

On the basis of magnetic field measurements around the Mars 2020 testbed drill, the M-2020 project accepted a requirement that the drilled cores will not experience fields exceeding the 0.5 mT requirement. This ensures that most ferromagnetic grains in the samples will not be remagnetized by spacecraft fields.

Mechanical Integrity and Internal Movement: The fracturing of a rock sample does not directly affect its scientific utility, as long as the pieces stay together (after all, once the MSR samples arrive at Earth, they will be deliberately broken into small pieces for the purpose of sample allocation). Although this was discussed at the 2014 Sample Quality Workshop, a viable approach to structuring a meaningful and achievable requirement was not identified at the time. Through discussions between the Mars 2020 project scientist and a pre-RSSB focus group, agreement was reached on a size-frequency distribution, which would have enough large pieces (>70%) to support the high-priority preparation of polished thin sections, enough medium-sized pieces (>20%) for many kinds of geochemical investigations and would minimize the quantity of "fines" (<10%), which are far less useful. Note that since different rocks have different strength, it was necessary to define this requirement with respect to a reference rock, which was selected to be a specific variant of the Bishop Tuff.

The movement of fragments of a rock relative to each other in the core is generally considered to be more damaging to science than fracturing itself. A fractured rock can be reconstructed if the pieces are still together. However, it was found to be impossible to write defensible requirements relating to distances or angles of movement of the multiple particles relative to each other. An alternate approach of minimizing the free volume inside the sample tubes was adopted—this would have the indirect effect of minimizing movement. In addition, the material of the tubes was chosen in part to allow X-ray CT scanning before opening, which may assist in understanding fragmentation, internal rotations, and displacements.

Temperature: The RSSB conducted an intensive analysis of temperature constraints for 11 investigations where thermal excursions could affect the outcome. A maximum temperature of 60 °C (20° above ambient temperature) was determined for samples within core tubes on the Martian surface and during recovery on Earth. Lower temperatures of 40–50 °C are desirable for investigations of organic matter, amorphous materials, hydrated sulfates and zeolites, and these lower temperatures can be satisfied for landing sites in the northern hemisphere without additional effort (Beaty et al. 2016). Temperature excursions during drilling can be mitigated by duty cycling. In response to this study, M-2020 Project engineers modified the core tube design to achieve this temperature constraint at all the putative Mars landing sites.

Mars-sourced contamination: Because the Mars 2020 rover will reuse drill bits, and not have the ability to clean between their sampling uses, cross contamination between Mars samples is inevitable. This was discussed at the 2014 Sample Quality Workshop, and agreement was reached that for most of the kinds of scientific questions of MSR, and for a series of samples that

Fig. A3.1. A returnable Mars 2020 sample tube assembly with a schematic illustration of a collected core. On the left is the interface with the drill, on the right is the open end of the tube, which is shown in this drawing after the hermetic seal has been installed. The rock sample (tan color) is shown schematically, but we expect almost all samples to be fractured, and in some cases, heavily so. Total length of the tube is ~15 cm. The sample cavity is ~13.2 mm × 100 mm, while the inner diameter (ID) of the cutting bit is 13 mm, resulting in an average size of collected cores of slightly less than 13 mm diameter. In tests on a range of analog materials the average size of collected cores was ~13 mm in diameter × 60 mm in length.

come from a single type of geologic terrane, a cross contamination limit of 1% would be compatible with most kinds of geochemistry studies.

Sealing: Volatiles in the sample, either bound in minerals, or adsorbed on mineral surfaces, may be released during storage of core tubes on the Martian surface. Sealing of the tubes is critical to retain volatiles, so that the original volatile inventory will be measured and the original states of volatiles can be calculated from thermodynamic considerations and from atmospheric samples that would be obtained as part of a follow-on retrieval mission. The tubes will also contain some headspace atmospheric gas. The limit is based on the leak rate for He for a 20-year residence on Mars.

Radiation: A radiation limit of 100 krad was proposed—this is approximately the natural dose the samples would receive if they spent 20 years in Mars orbit. Additional sample irradiation beyond that is in general considered undesirable, although this is a relatively low dose and specific adverse effects caused by exceeding it by a small amount have not been identified.

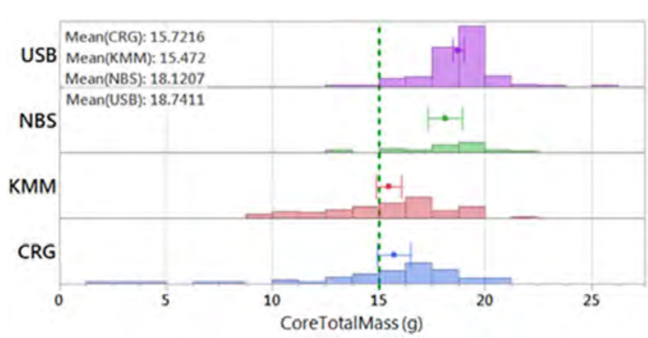

Fig. A3.2. Summary of sample mass recovered during drill testing on rocks, using four different terrestrial analog rock types. The four lithologies were a basalt (USB), a basaltic sandstone (NBS), a mudstone (KMM), and a gypsum (CRG).

Mars 2020 Sample Caching Capabilities: The rover's drill will use rotary motion with or without percussion to penetrate Martian rock to collect samples directly into clean sample tubes. The ID of the drill bit is 13.0 mm and the ID of the sample tubes is 13.2 mm x 100 mm in length (the internal volume of the tubes is therefore 13.25 cm^3) (Fig. A3.1). Our best estimate of the expected size of the returned samples comes from Fig. A3.2, which shows the results of the brassboard corer development testing program using analog samples. There were significant differences in sample masses collected across different rock types, and even within a single rock type there were a range of recovered sample masses. In summary, the findings were that (1) the overall average sample mass was 16.5 g; (2) 90% of samples collected were >13.4 g; (3) a significant fraction of samples were as large as ~20 g and; (4) there were only a few that were classified as engineering failures (<5 g). The collected cores were typically ~12.7 mm in diameter and about 60 mm long. Note that Martian rocks will be different than these terrestrial analogs, the flight drill will not be identical to the test unit, and there will be operational differences, so the above statistics are only useful as a guideline. After imaging and evaluating the volume of collected material, each tube will be hermetically sealed on Mars for eventual deposit in cache depots on the Martian surface.

Mars 2020 will carry total of 42 tubes, of which 5 (witness blank tubes) will be flown preloaded with a range of witness materials designed to accumulate molecular and particulate contaminants. These witness tubes will be sealed, cached on the Martian surface, and

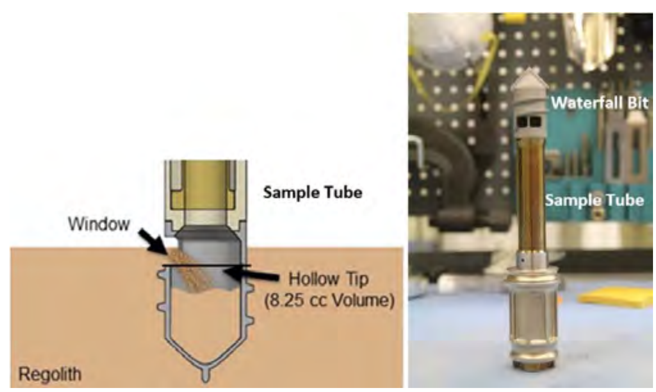

Fig. A3.3. Left—Schematic drawing of the M-2020 waterfall drill bit, for use in collecting granular material. The bit action consists of rotation just below the Martian surface, and material entry into the bit through the side windows. Right—After collection the drill bit and attached sample tube are carefully reoriented to allow the sample to move from the drill bit into the sample tube.

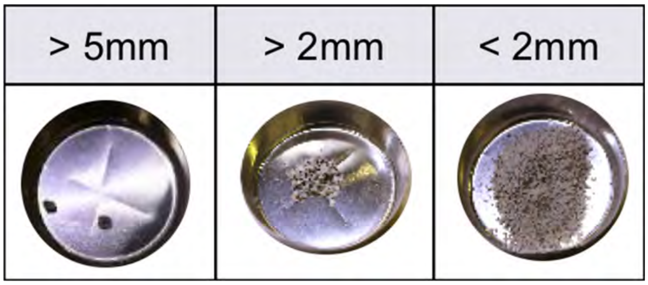

Fig. A3.4. As shown by this test result using a regolith simulant, the waterfall bit can collect small rocks with size >5 mm, potentially larger numbers of very small rocks >2 mm, and bulk fines. The actual particle size distribution of the M-2020 samples will of course depend on the nature of the material sampled.

potentially returned to Earth together with the Martian samples for analysis in terrestrial laboratories. Witness blanks are an important part of the Mars 2020 strategy to provide a mechanism for characterization of the round-trip terrestrial contamination. Round-trip blanks/controls are widely accepted by the science community as a good method to mitigate the fact that terrestrial contaminants at low levels cannot be eliminated entirely from the hardware. Characterization of the molecular and particulate contamination captured by the witness blanks is necessary for distinguishing Earth-sourced contaminants from the Martian signal.

Besides core samples, Mars 2020 will collect samples of granular materials using a specially designed bit (Fig. A3.3), referred to as a "waterfall" bit. This bit has a closed end and openings on the side. Using the drill, the bit will be slowly spun down into the Martian soil, producing an inward cascade of the particles into two rectangular window openings 8 mm tall × 7.4 mm wide. The internal volume of the sample cavity below the level of the windows is 8.25 cm^3 (see Fig. 3.3A.). Inverting the drill will pour the collected material into the sample tube and, subsequently, it will be hermetically sealed in the same manner as the core samples. Because of the cascading action of the granular material both into and out of the drill bit, all semblance of original stratification is expected to be lost. The Level 4 requirement is that the bit be able to collect 8 cm^3 of regolith material and experimental studies confirm that this can be achieved. Based on analogy with lunar regolith, and data from bulk fines sampled by Viking, the density of disturbed Martian regolith was estimated by E2E-iSAG (2012) to be about 1.15 g cm^{-3}. A fully filled waterfall bit, therefore, can be expected to contain about 9.5 gm of material. Because of the nature of the window openings in the bit, it will exclude rock fragments larger than about 8 mm, thereby potentially size-fractionating the sample. However, the design is such that it will collect samples with a range of grain size, so we can reasonably expect the samples to have a grain size distribution analogous to that shown in Fig. A3.4.

APPENDIX 4: GLOSSARY OF ACRONYMS

ALH	Allan Hills
AMS	Accelerator Mass Spectrometry
APXS	Alpha Particle X-Ray Spectrometer, an instrument carried on both the MER and MSL missions
CEC	Cation Exchange Capacity
CHEMIN	Chemistry and Mineralogy instrument, an instrument on the MSL mission
CONICET	Consejo Nacional de Investigaciones Científicas y Técnicas
COSPAR	Committee on Space Research
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars, an instrument on the MRO mission
CT	Computerized Tomography
DAN	Dynamic Albedo of Neutrons, an instrument on the MSL mission
E2E-iSAG	End-to-End International Science Analysis Group
EFA	Elementally Fractionated Air
EFM/EFMA	Elementally Fractionated Martian Atmosphere
Eh	Redox potential
EMPA	Electron Microprobe Analysis
EPS	Exopolymeric Substance
ESA	European Space Agency
ExoMars	A Mars rover mission scheduled for launch in 2020
FTIR	Fourier Transform-Infrared Spectroscopy
GCR	Galactic Cosmic Rays
GS-MS (GC-MS)	Gas Chromatography-Mass Spectrometry
HSE	Highly Siderophile Elements
iMARS	International Mars Architecture for the Return of Samples, a planning committee chartered by IMEWG that was active in 2007-08.
IMEWG	International Mars Exploration Working Group
iMOST	International Mars Sample Return Objectives and Samples Team, a planning committee chartered by IMEWG that was active in 2017-18.
IR	Infrared
IS	Investigation Strategy
ISRU	In Situ Resource Utilization
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory

Appendix. *Continued.* Glossary of Acronyms

KREEP	Potassium, Rare Earth Element and Phosphorus
LA-MS	Laser Ablation Mass Spectrometry
LIBS	Laser-Induced Breakdown Spectroscopy
M-2020	Mars 2020, a Mars rover mission scheduled for launch in 2020
MAHLI	Mars Hand Lens Imager, an instrument on the MSL mission
MAVEN	Mars Atmosphere and Volatile Evolution, a Mars orbiter mission launched in 2013
MEPAG	Mars Exploration Program Analysis Group
MEX	Mars Express, a Mars orbiter mission launched in 2003
MGS	Mars Global Surveyor, a Mars orbiter mission launched in 1996
MRO	Mars Reconnaissance Orbiter, a Mars orbiter mission launched in 2005
MS	Mass Spectrometry
MSR	Mars Sample Return
MSL	Mars Science Laboratory, a Mars rover mission launched in 2011
MWIP	Mars Water ISRU Planning, a planning committee chartered by NASA that was active in 2016.
NASA	National Aeronautical and Space Administration
NRC	National Research Council, an organization within the U.S. National Academy of Science
NWA	Northwest Africa, a designation used for many Mars meteorites
OCP	Organic Contamination Panel, a planning committee chartered by NASA that was active in 2014
PBS	Potential Biosignature
PGM	Platinum Group Metals
PIXL	Planetary Instrument for X-ray Lithochemistry, an instrument on the M-2020 mission
PP	Planetary Protection
REE	Rare Earth Elements
REMS	Rover Environmental Monitoring Station, an instrument on the MSL mission
RIMFAX	Radar Imager for Mars' Subsurface Experiment, an instrument on the M-2020 mission
RSL	Recurring Slope Lineae
RSSB	Returned Sample Science Board
SAM	Sample Analysis at Mars, an instrument on the MSL mission
SDT	Sample Definition Team
SEM	Scanning Electron Microscopy
SHERLOC	Scanning Habitable Environments for Raman and Luminescence, an instrument on the M-2020 mission
SSB	Space Studies Board, a standing committee of the U.S. National Academy of Science
STEM	Scanning Transmission Electron Microscopy
TES	Thermal Emission Spectroscopy
TGO	Trace Gas Orbiter, a Mars orbiter mission launched in 2016
TIMS	Thermal Ionization Mass Spectrometry
TLS	Tunable Laser Spectrometer, an instrument on the MSL mission
TOC	Total Organic Carbon
WEH	Water-equivalent Hydrogen
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

APPENDIX 5: GLOSSARY OF DEFINITIONS OF SIGNIFICANT TERMS

Note that some partial-acronyms, i.e., phrases including acronyms, are listed here. In general, some key mineral group names are listed, but specific phases are not.

Acetyl-CoA pathway—Set of biochemical reactions used by some bacteria and archaea called acetogens. Also known as the Wood–Ljungdahl pathway.

Aeolian—Pertaining to a process or feature formed by the movement of an atmosphere interacting with a bodies' surface.

Allogenic—Originated from eroded ancient crust.

Alteration halo—A border of minerals produced by hydrothermal alteration in the rock surrounding a vein.

Amazonian—Most recent Martian geologic epoch, dominated by hyperarid, cold conditions, and low meteorite and asteroid impact rates. Generally accepted to span from 3.0 Ga to present day.

Anaerobic—Relating to or requiring an absence of free oxygen.

Anhedral—[Of minerals] to have no defined crystal faces, or cross-sectional shape in thin section.

Authigenic—In situ newly formed minerals in a deposit by various chemical reactions.

Breccia—Rock comprised of angular fragments of stones cemented by finer calcareous material.

CheMin—Chemistry and Mineralogy X-diffraction instrument aboard NASA's Mars Science Laboratory Rover.

Chemosynthetic pathways—Use of energy released by inorganic chemical reactions for nutrition.

Chemolithotroph—Organism that uses inorganic reduced compounds for energy.

***Chemotrophic*—**[of organisms] to obtain energy by the oxidation of electron donors.

***Clastic*—**A type of sedimentary rock or sediment. Clastic rocks are accumulations of transported weathering debris that have been lithified.

***Concretion*—**Feature formed when water carries dissolved minerals through sediments or porous rocks and minerals precipitate such that surrounding sediments are incorporated or replaced.

***Conglomerate*—**Clastic sedimentary rock containing rounded clasts >2 mm diameter. Inter-clast space is generally filled with smaller particles and/or a calcite or quartz cement.

***Cosmogenic nuclides*—**Nuclides (isotopes) created when high-energy cosmic rays interact with nuclei, causing nucleons to be expelled.

***Crystal mold*—**Diagnostically shaped cavity left in rock after dissolution of a crystal of a specific mineral phase.

***Deltaic*—**Of or like a river delta.

Diagenesis*—Process of sediment modification postdeposition, including cementation, compaction, leaching, and replacement, but excluding weathering and metamorphism.*

Epithermal*—[of mineral veins and ore deposits]* Deposited from warm waters at shallow depth at relatively low temperature and pressure (compared to the higher pressure and temperatures in hypothermal and mesothermal environments).

***Evaporites*—**Water-soluble mineral sediment that results from concentration and crystallization by evaporation from an aqueous solution.

***Facies*—**The character of a rock expressed by its formation, composition, and fossil content.

***Filamentous*—**of a slender object or fiber, particular those found in plant or animal structures.

***Feldspar*—**Mineral in the feldspar group ($KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$) of rock-forming tectosilicate minerals. Feldspars are ~41 wt% of the Earth's continental crust. Feldspar-bearing rocks are said to be Feldspathic.

***Fractional crystallization*—**The removal of early-formed crystals from an originally homogeneous magma (for example, by gravity settling) so that these crystals are prevented from further reaction with the residual melt. The composition of the remaining melt becomes relatively depleted in some components and enriched in others, resulting in the precipitation of a sequence of different minerals.

***Fumarole*—**Volcanic vent from which gases emerge.

***Geochronology*—**Study of age determination of rocks, fossils and sediments using stable- or radioisotope ratios for relative and absolute dating, respectively.

***Hesperian*—**Middle Martian geologic epoch characterized by volcanic activity and catastrophic flooding events. Broadly accepted to span 3.7–3 Ga.

***Hydraulic fracturing*—**Fracturing of rock by a pressurized fluid.

***Inorganic carbon*—**the boundary between "organic" and "inorganic" carbon is ambiguous, and no single definition is broadly accepted. Here we use "inorganic" to refer primarily to materials comprised of oxygen and carbon. Examples include gaseous CO and CO_2, dissolved CO_3^{2-} and HCO_3^{-}, and carbonate minerals such as calcite and dolomite. Many definitions of inorganic carbon also include metal and metalloid carbides, cyanides, and elemental carbon, although for clarity we refer here to such materials specifically by name rather than as inorganic carbon.

***Ion microprobe*—**Analytical instrument that applies a stable and focused beam of charged particles to a sample such that the elemental composition of the sample can be determined via analysis of the emitted X-rays (if the primary beam is electrons), or of the secondary beam of material sputtered from the target (if the primary beam is ions).

***Isotopes*—**Atoms of the same element having a different number of neutrons, and hence mass. They are chemically identical and form the same compounds, phases, etc., but the mass difference causes them to react at subtly different rates. Radioactive versus stable isotopes (^{14}C versus ^{13}C, ^{3}H versus ^{2}H) are frequently distinguished, and the relative abundance of certain isotopes (in organic matter, primarily ^{2}H, ^{13}C, ^{15}N, ^{18}O, and ^{34}S) are frequently used to distinguish between materials of terrestrial versus extraterrestrial origin.

***Isotopic fractionation*—**any chemical, physical, or biological process that alters the relative abundance of isotopes in a material. An example is the depletion of ^{2}H and ^{18}O in water vapor evaporating from a liquid. Many natural processes have characteristic isotopic fractionations, e.g., fixation of CO_2 in the photosynthesis. The loss of radioactive isotopes (e.g., ^{14}C or ^{3}H) due to decay is not typically regarded as fractionation as it occurs regardless of physical or chemical processes.

***Lacustrine*—**Relating to lake environments.

***Lagerstätte*—**Sedimentary deposit that exhibits extraordinary fossils with exceptional preservation, possibly including preserved soft tissues.

***Laminations*—**Thin layering in sedimentary rocks.

***Laser Ablation [Mass Spectrometry]*—**Analysis technique that uses laser illumination of a sample to ablate material such that the fine ablation products can then be analyzed in a mass spectrometer.

Leaching**—**Removal of soluble substances and colloids from upper soil layers by downward percolating precipitation.

Macromolecular organic carbon**—**complex, high molecular weight, organic carbon compounds which are formed by polymerization or cross-linking of smaller subunits. Organic macromolecules include ordered biopolymers such as proteins, DNA, polysaccharides, and lignin; synthetic polymers including polyester, polytetrafluoroethylene (Teflon), and silicone; and irregular geopolymers such as humic acids, asphaltenes, and kerogen.

Mafic**—**Of a silicate mineral or igneous rock that is rich in magnesium and iron (a portmanteau of magnesium and ferric). Most mafic minerals are dark in color, and common rock-forming mafic minerals include olivine, pyroxene, amphibole, and biotite. Common mafic rocks include basalt, diabase and gabbro.

Matric potential**—**Component of water potential due to the adhesion of water molecules to nondissolved structures of the system, i.e., the matrix, such as plasma membranes or soil particles.

Meteoric**—**[of water] derived from precipitation.

Methanogen**—**Organism that produces CH_4 as a result of its metabolism.

Mössbauer spectroscopy**—**Analysis technique utilizing the nearly recoil-free, resonant absorption, and emission of gamma rays in solids.

Noachian**—**Early Martian geologic epoch characterized by a higher impact flux, and evidence for abundant surface water. Broadly accepted to span 4.1–3.7 Ga.

Olivine**—**Magnesium iron mineral group with the general formula $(Mg^{2+}, Fe^{2+})_2 SiO_4$. It is nesosilicate, or orthosilicate. Mg-rich olivine crystallizes from magma that is rich in magnesium and low in silica. Olivine occurs in both mafic and ultramafic igneous rocks and as a primary mineral in certain metamorphic rocks.

Opaline silica**—**A form of hydrated silica that can be formed in hydrothermal settings, and on Earth can have bio-mediated formation.

Organic carbon**—**for the purposes of this report, any carbonaceous substance that is not inorganic. Typical definitions include the presence of covalent C-C and/or C-H bonds, average oxidation state <4, yielding CO_2 upon combustion, and others. All of these definitions comprise (different) subsets of the broader definition that we adopt here. Examples include formic acid, ethanol, glucose, hydrocarbons including methane, lipids, amino acids, purines, pyrimidines, urea, chlorofluorocarbons, Teflon, dimethylsilicone, etc. The term organic carbon does not imply formation by a biological process.

Organic particulates**—**macromolecular organic material that can be captured by sieving filters (for example >1 μm particulates).

Osmotic potential**—**The potential of water molecules to move from a hypotonic solution (more water, less solutes) to a hypertonic solution (less water, more solutes) across a semi permeable membrane.

Ostwalkd ripening**—**The change of an inhomogeneous structure over time such that small crystals or particles dissolve and redeposit onto larger crystals or particles.

Paleoclimate**—**Historial climate recorded in sediments.

Paleosol**—**A stratum formed as a soil in a past geologic age.

Paragenetic sequence**—**Chronologically ordered set of mineral phases formed successively from a starting chemical equilibrium.

Phase assemblage**—**A set of coexisting minerals. Meaning is on emphasis of their co-mediated genesis.

Phyllosilicates**—**A major rock-forming mineral group formed of sheets of Si_2O_5 tetrahedra. Also known as clay minerals. All are hydrated and thus their existence indicates the presence of water in their formative environment.

Pre-biotic chemistry**—**Organic or inorganic chemistry occurring naturally before the advent of life on the Earth.

Penecontemporaneous**—**Of a process occurring immediately the deposition of a stratum.

Planetesimals**—**Solid object arising during the accumulation of planets whose internal strength is dominated by self-gravity and whose orbital dynamics is not significantly affected by gas drag.

Playa**—**[of deposits or environment] flat land mediated by saturation followed by dessication. Playa deposits may contain evaporite minerals or geologic textures resulting from many of these cycles.

Phototrophic**—**[of an organism] obtaining energy from sunlight to synthesize organic compounds for nutrition.

Phylogenetic**—**Pertaining to evolutionary relationships between biological entities.

Provenance**—**[of a lithology] the original composition of the igneous, metamorphic, or sedimentary source rocks.

Pyroxene**—**Group of common rock-forming minerals with a structure defined by single chains of silica tetrahedra (inosilicates). Pyroxenes have the general formula $[X][Y](Si,Al)_2O_6$.

Radiolysis**—**The dissociation of molecules by ionizing radiation.

Raman spectroscopy—Measurement of wavelength and intensity of inelastically scattered light from molecules. Raman scattered light occurs at wavelengths that are shifted from the incident light by the energies of molecular vibrations.

Regolith (the reason for this is that there is more than one definition of regolith, and its relationship to the lay term "soil" is confusing).

Sabkha—Area of coastal flats subject to periodic flooding and evaporation, resulting in accumulation of aeolian clays, evaporites, and salts.

Saltation—Transport of solid particles over a surface due to forces imparted by a turbulent fluid.

Shergottite—Meteorite belonging to a group defined by the type-specimen Shergotty, which fell in India in 1865. It is composed mostly of pyroxene, solidified from a Martian magma at ~4.1 Ga, but was subsequently aqueously altered.

Siliceous—[Of rocks] having silica, SiO_2, as the principle component.

Sinter (geologic material)—The product of natural fusing processes, using heat, pressure, and chemistry, that do not require melting.

Stratigraphic—Relating to layering in sedimentary rocks.

Stromatolite—Rocks formed by fossilized bacteria and their products. These are associated with early forms of life on Earth.

Subaerial, subaqueous, subglacial—Refer to processes occurring within and mediated by the atmosphere, water, or ice, respectively.

Synchrotron—Ring-based particle accelerator producing X-rays used for analysis, including to identify mineral phases in geologic materials by X-ray diffraction.

Taphonomy—Study of the fossilization process.

Tephra—Rock fragments and particulates erupted by volcanic processes.

Thermal skin depth—The distance, δ, over which the effect of a thermal wave of period, P, reduces by a factor of 1/e. Given by: $\delta = (\kappa P/\rho c \pi)^{1/2}$, where κ is the thermal conductivity, ρ is the density and c is the specific heat capacity.

Travertine—Form of limestone precipitated from mineral-rich water.

Ultramafic—Igneous and meta-igneous rocks with a very low silica content (<45%). Composed of usually >90% mafic minerals. Earth's mantle is composed of ultramafic rocks.

Volcaniclastic—Term used to describe all particles originating from volcanic eruptive processes.

Vug—Cavity in a rock formed by tectonic processes. Can be filled with secondary minerals.

Weathering rind—Discolored, chemically altered, outer zone or layer of a discrete rock fragment formed by the processes of weathering.