An Astrobiology Strategy for the EXPLORATION *of* MARS

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

An Astrobiology Strategy for the EXPLORATION *of* MARS

Committee on an Astrobiology Strategy for the Exploration of Mars

Space Studies Board
Division on Engineering and Physical Sciences

Board on Life Sciences
Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS **500 Fifth Street, N.W.** **Washington, DC 20001**

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract NASW-01001 between the National Academy of Sciences and the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the agency that provided support for the project.

International Standard Book Number-13: 978-0-309-10851-5
International Standard Book Number-10: 0-309-10851-9

Cover design by Penny E. Margolskee. Images courtesy of National Aeronautics and Space Administration/Jet Propulsion Laboratory.

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

Additional copies of this report are also available for purchase from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

OTHER REPORTS OF THE SPACE STUDIES BOARD

Building a Better NASA Workforce: Meeting the Workforce Needs for the National Vision for Space Exploration (2007)
Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond (2007)
Exploring Organic Environments in the Solar System (SSB with the Board on Chemical Sciences and Technology, 2007)
A Performance Assessment of NASA's Astrophysics Program (SSB with the Board on Physics and Astronomy, 2007)

An Assessment of Balance in NASA's Science Programs (2006)
Assessment of NASA's Mars Architecture 2007-2016 (2006)
Assessment of Planetary Protection Requirements for Venus Missions: Letter Report (2006)
Distributed Arrays of Small Instruments for Solar-Terrestrial Research: Report of a Workshop (2006)
Issues Affecting the Future of the U.S. Space Science and Engineering Workforce: Interim Report (SSB with the Aeronautics and Space Engineering Board [ASEB], 2006)
Review of NASA's 2006 Draft Science Plan: Letter Report (2006)
The Scientific Context for Exploration of the Moon—Interim Report (2006)
Space Radiation Hazards and the Vision for Space Exploration (2006)

The Astrophysical Context of Life (SSB with the Board on Life Sciences, 2005)
Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation (2005)
Extending the Effective Lifetimes of Earth Observing Research Missions (2005)
Preventing the Forward Contamination of Mars (2005)
Principal-Investigator-Led Missions in the Space Sciences (2005)
Priorities in Space Science Enabled by Nuclear Power and Propulsion (SSB with ASEB, 2005)
Review of Goals and Plans for NASA's Space and Earth Sciences (2005)
Review of NASA Plans for the International Space Station (2005)
Science in NASA's Vision for Space Exploration (2005)

Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report (SSB with ASEB, 2004)
Exploration of the Outer Heliosphere and the Local Interstellar Medium: A Workshop Report (2004)
Issues and Opportunities Regarding the U.S. Space Program: A Summary Report of a Workshop on National Space Policy (SSB with ASEB, 2004)
Plasma Physics of the Local Cosmos (2004)
Review of Science Requirements for the Terrestrial Planet Finder: Letter Report (2004)
Understanding the Sun and Solar System Plasmas: Future Directions in Solar and Space Physics (2004)
Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond (SSB with ASEB and the Board on Atmospheric Sciences and Climate [BASC], 2004)

Limited copies of these reports are available free of charge from:

Space Studies Board
National Research Council
The Keck Center of the National Academies
500 Fifth Street, N.W., Washington, DC 20001
(202) 334-3477/ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release, which in some cases precedes the year of publication.

COMMITTEE ON AN ASTROBIOLOGY STRATEGY FOR THE EXPLORATION OF MARS

BRUCE M. JAKOSKY, University of Colorado, *Chair*
JAN P. AMEND, Washington University in St. Louis
WILLIAM M. BERELSON, University of Southern California
RUTH E. BLAKE, Yale University
SUSAN L. BRANTLEY, Pennsylvania State University
MICHAEL H. CARR, U.S. Geological Survey (retired)
JAMES K. FREDRICKSON, Pacific Northwest Research Laboratory
ANTHONY D. KEEFE, Archemix Corporation
MARTIN KELLER, Oak Ridge National Laboratory
HARRY Y. McSWEEN, University of Tennessee
KENNETH H. NEALSON, University of Southern California
BARBARA SHERWOOD-LOLLAR, University of Toronto
ANDREW STEELE, Carnegie Institution of Washington
ROGER E. SUMMONS, Massachusetts Institute of Technology
MEENAKSHI WADHWA, Arizona State University

Staff

DAVID H. SMITH, Study Director
ROBERT L. RIEMER, Senior Program Officer
RODNEY N. HOWARD, Senior Project Assistant
CATHERINE A. GRUBER, Assistant Editor
ANGELA BABER, Research Assistant
EMILY McNEIL, Research Assistant

SPACE STUDIES BOARD

BOARD ON LIFE SCIENCES

Preface

Scientific strategies for the exploration of Mars have been defined in recent years by various groups, including both the National Research Council (NRC) and NASA. The findings and recommendations of the Space Studies Board's reports *Assessment of Mars Science and Mission Priorities* (2003) and *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003) are broadly consistent with the priorities outlined in the report of NASA's Mars Exploration Program Analysis Group (MEPAG), *Scientific Goals, Objectives, Investigations, and Priorities: 2004*. Although all three reports agreed that highest priority should be assigned to determining if living organisms ever arose on Mars, their timing was such that new insights arising from the biological sciences (e.g., insights based on studies of organisms that thrive on Earth under extreme conditions and on developing techniques arising from molecular biology and biotechnology) did not play a prominent role in their authors' deliberations. Rather, all three groups considered the search for life in the context of the origin and evolution of the martian environment. Now, with the benefit of several additional years of maturation, the time is right to attempt a new synthesis of ideas on the search for life on Mars that integrates input from both the life sciences and the environmental sciences communities. Indeed, *Signs of Life* (2002), the report of a Space Studies Board workshop, demonstrated that both new evidence and new techniques are available to assist the search for life on Mars, and the report advocated furthering the research on and development of emerging technologies and incorporating both emerging and developed technologies into the astrobiological search for life.

Although NASA's MEPAG has been particularly active in the last few years in defining the key environmental issues relating to the search for life on Mars, NASA's most recent end-to-end strategy for the detection of martian life, *An Exobiological Strategy for Mars Exploration*, was published in 1995. The corresponding European Space Agency strategy, *Exobiology in the Solar System and the Search for Life on Mars*, was published in 1999.

Clearly, the various ideas and concepts encompassing the biological and environmental perspectives relevant to the search for martian life developed in a diversity of reports published between 1995 and 2004 were ripe for integration. The Committee on the Origins and Evolution of Life (COEL)—a joint undertaking of the NRC's Space Studies Board and Board on Life Sciences charged with maintaining oversight on issues relating to astrobiology—discussed such a possibility extensively during several of its meetings in 2004 and in early 2005 persuaded NASA officials that the time was right for a study integrating the various Mars exploration strategies and life-detection concepts into a single, coherent picture.

As a result of COEL's activities and other factors, Mary L. Cleave, then NASA's associate administrator for the Science Mission Directorate, sent a letter to Lennard A. Fisk, chair of the Space Studies Board, on September 13, 2005, requesting assistance "in developing an up-to-date integrated astrobiology strategy for Mars exploration that brings together all the threads of this diverse topic into a single source for science mission planning . . . ."

Dr. Cleave's request was passed back to COEL and discussed extensively during a meeting held at the Southwest Research Institute in Boulder, Colorado, on October 3-5, 2005. As a result of COEL's discussions and deliberations, a plan of action was developed that resulted in the formal appointment in January 2006 of the ad hoc Committee on an Astrobiology Strategy for the Exploration of Mars.

The committee met for the first time at the National Academies' Beckman Center in Irvine, California, on January 23-25, 2006. Work continued at meetings held at the National Academies' Keck Center in Washington, D.C. (May 10-12), the University of Colorado's Laboratory for Atmospheric and Space Physics in Boulder, Colorado (September 13-15), and the National Academies' J. Erik Jonsson Center in Woods Hole, Massachusetts (November 8-10). A draft report was completed in early December and sent to external review in mid-December. A new draft responding to the reviewers' comments was completed in late January 2007, and the report was approved for release in May 2007.

The work of the committee was made easier thanks to the important help, advice, and comments provided by numerous individuals from a variety of public and private organizations. These include the following: Marc Allen (NASA, Science Mission Directorate), Mark Allen (NASA, JPL), Ariel Anbar (Arizona State University), Jillian Banfield (University of California, Berkeley), John Baross (University of Washington), David Beatty (NASA, JPL), Luann Becker (University of California, Santa Barbara), Luther Beegle (NASA, JPL), Klaus Biemann (Massachusetts Institute of Technology), David Catling (University of Bristol), Barbara Cohen (University of New Mexico), David DesMarais (NASA, Ames Research Center), Christopher M. Fedo (University of Tennessee), Matthew Golombeck (NASA, JPL), Ronald Greeley (Arizona State University), Andrew Knoll (Harvard University), Paul R. Mahaffy (NASA, Goddard Space Flight Center), Michael Malin (Malin Space Science Systems), Michael Meyer (NASA, Science Mission Directorate), Jack F. Mustard (Brown University), Tullis C. Onstott (Princeton University), Carl Pilcher (NASA Astrobiology Institute), Susannah Porter (University of California, Santa Barbara), John Rummel (NASA, Science Mission Directorate), Bruce Runnegar (NASA Astrobiology Institute), Alan Treiman (Lunar and Planetary Institute), Ashwin R. Vasavada (NASA, JPL), Frances Westall (Centre de Biophysique Moleculaire, CNRS), and Richard W. Zurek (NASA, JPL).

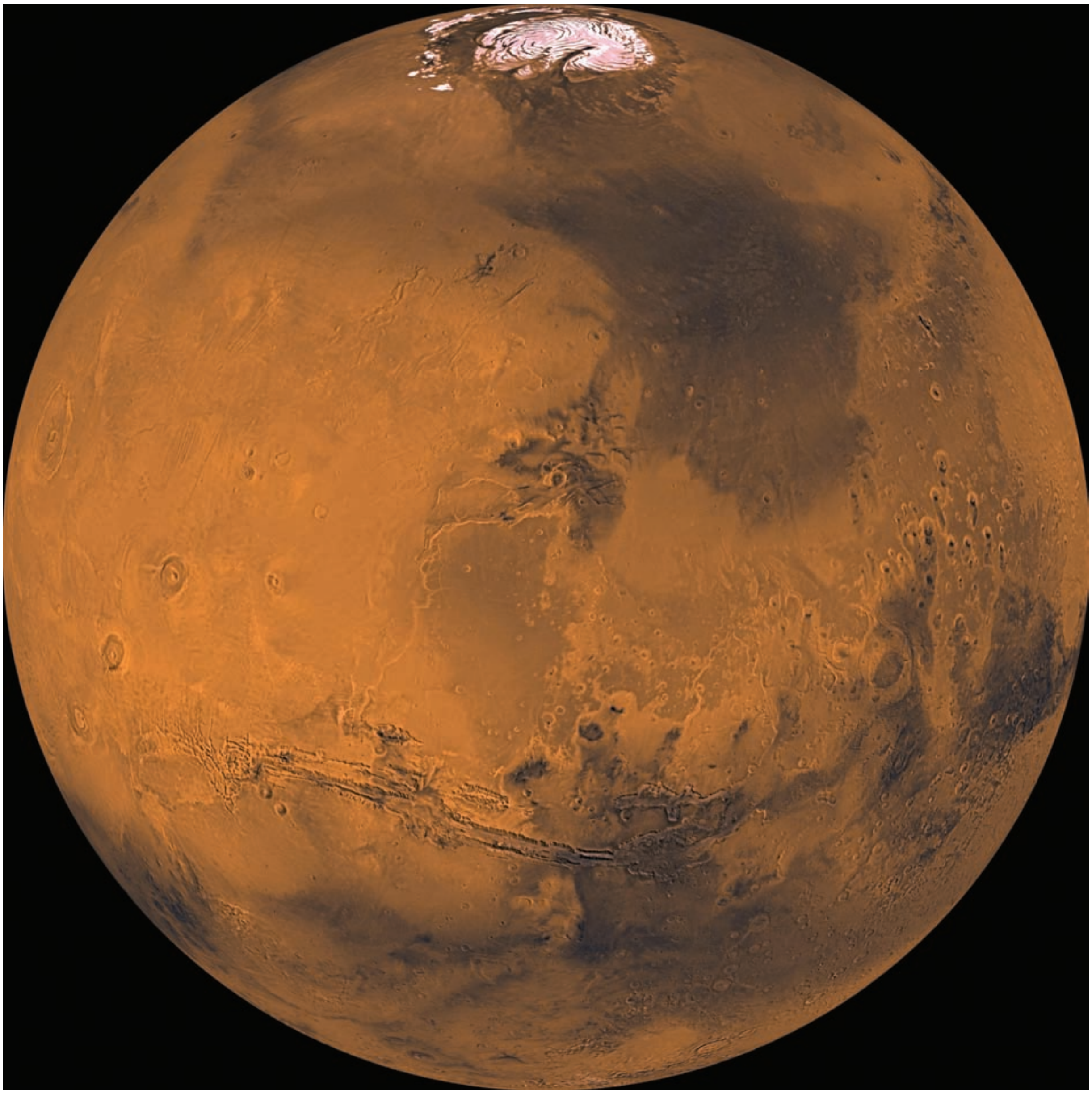
This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The committee wishes to thank the following individuals for their participation in the review of this report: Robert D. Braun (Georgia Institute of Technology), Charles S. Cockell (The Open University), John Kerridge (University of California, San Diego), Alfred S. McEwen (University of Arizona), Hiroshi Ohmoto (Pennsylvania State University), Norman R. Pace (University of Colorado), and Dawn Y. Sumner (University of California, Davis). Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Norman H. Sleep (Stanford University). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

An Astrobiology Strategy for the

EXPLORATION
of
MARS



This global image of Mars was made by piecing together about 1,000 images from the Viking orbiters. This view encompasses the north polar cap (top), the Valles Marineris (lower center), and the Tharsis volcanic region (left). This image and the lead figure in each chapter have been selected to illustrate the geological diversity of the martian environment. Image courtesy of NASA/JPL and the U.S. Geological Survey.

Executive Summary

From Mars Pathfinder to Mars Express, Mars Reconnaissance Orbiter, and the Mars Exploration Rovers *Spirit* and *Opportunity*, the recent spate of robotic missions to the Red Planet has led to a wealth of new information about the planet's environment, including strong evidence of a watery past and the possible discovery of atmospheric methane. In addition, new developments in our understanding of life in extreme conditions on Earth suggest the possibility of microbial viability in the harsh martian environment. Together, these results have greatly increased interest in the search for life on Mars, both within the scientific community and beyond.

Such scientific interest achieved a new focus on January 14, 2004, when President George W. Bush announced the new Vision for Space Exploration, directing NASA to focus its efforts on robotic and human exploration of space, particularly of the Moon and Mars. Included in the Vision is an explicit directive to "[c]onduct robotic exploration of Mars to search for evidence of life . . . ."

Given the enhanced scientific and political interest in the search for life on Mars, it is surprising that NASA's most recent end-to-end strategy for the detection of martian life, contained in the report *An Exobiological Strategy for Mars Exploration*, was published as long ago as 1995.

Against this backdrop, NASA's Science Mission Directorate requested the Space Studies Board's assistance in developing an up-to-date integrated astrobiology strategy for Mars exploration that brings together all the threads of this diverse topic into a single source for science mission planning. In particular, NASA asked that the strategy developed by the Committee on an Astrobiology Strategy for the Exploration of Mars address the following topics:

- The characteristics of potential targets for Mars exploration particularly suited for elucidating the prebiotic and possibly biotic history of Mars, and methods for identifying these targets;
- A catalog of biosignatures that reflect fundamental and universal characteristics of life (i.e., not limited to an Earth-centric perspective);
- Research activities that would improve exploration methodology and instrumentation capabilities to enhance the chances of astrobiological discovery; and
- Approaches to the exploration of Mars that would maximize the astrobiological science return.

THE SEARCH FOR LIFE ON MARS

Mars is the most logical place to look for life elsewhere in the solar system because it is the most Earth-like of all the other planetary bodies in terms of its geological environment and the availability of liquid water at or near the surface throughout time. Moreover, Mars is the most accessible planetary body other than the lifeless Moon. The finding of evidence for past or present life beyond Earth would have profound philosophical and scientific ramifications, and a finding either that life was present or that it was not would have dramatic implications for the prospects for life elsewhere in the universe.

The search for life on Mars requires a detailed understanding of the nature of life on Earth and how it functions in different environments. The search also requires a very broad understanding of Mars as an integrated planetary system. Such an integrated understanding requires investigation of the following:

- The geological and geophysical evolution of Mars;
- The history of Mars's volatiles and climate;
- The nature of the surface and the subsurface environments;
- The temporal and geographical distribution of liquid water;
- The availability of other resources (e.g., energy) that are necessary to support life; and
- An understanding of the processes that controlled each of the factors listed above.

Although it is not the only possible emphasis for the Mars program, astrobiology provides a scientifically engaging and broad approach that brings together multiple disciplines to address an important set of scientific questions that are also of tremendous interest to the public.

Finding. **The search for evidence of past or present life, as well as determination of the planetary context that creates habitable environments, is a compelling primary focus for NASA's Mars Exploration Program.**

The astrobiology science goals for the exploration of Mars extend beyond the search for present and past life to encompass an understanding of the geological and environmental context that determines planetary habitability; habitability is defined as a general term referring to the potential of an environment (past or present) to support microbial life of any kind. Such an undertaking entails understanding the geological and geochemical evolution of the planet, its internal structure, and the nature of its interaction with the space environment. Such a broad approach will likely be required to enable astrobiologists to determine which characteristics of martian materials result from nonbiological processes and which result from biological processes and so could be used as biosignatures.

Any comprehensive program focusing on the astrobiological exploration of Mars must be undertaken with the full understanding that the outcome is uncertain. It is entirely possible that surface water did not survive on Mars for a period of time sufficient for an origin of life, or that Mars never had life. Astrobiologists seek to explore Mars to better understand the nature of the planet, to assess its biological potential and habitability, and to determine how far chemical evolution proceeded and whether life was present. A finding of "no life" would be just as important scientifically as a finding of life, in terms of constraining our views of how life originates and spreads and of how widespread life might be in the universe.

NASA's 1995 report *An Exobiological Strategy for Mars Exploration* took the approach of starting from the global perspective and focusing increasingly on the local perspective. This approach involved a series of steps:

1. Global reconnaissance that focused on the history of water and the identification of sites for detailed in situ analysis;
2. In situ analysis at sites that hold promise for understanding the history of water;
3. Deployment of experiments that address astrobiology science questions, including the nature of martian organic molecules and the presence of features indicative of present-day or prior life;
4. Return of martian samples to Earth for detailed study; and
5. Human missions that would provide the detailed geological context for astrobiology measurements and the detection of modern-day "oases" for life.

This reasoned and measured approach provides the best opportunity for determining the geological and geochemical context in which the most useful and appropriate astrobiological measurements can be determined, implemented, and then properly interpreted and understood. It combines a broad, interdisciplinary approach to understanding Mars as a whole with the detailed, focused investigations that allow researchers to understand the astrobiology of Mars.

Finding. **The search for life and understanding the broad planetary context for martian habitability will require a broad, multidisciplinary approach to Mars exploration.**

Finding. **At the same time, the astrobiological science goals can best be addressed by an implementation that allows researchers to address increasingly focused questions that relate to astrobiology goals in particular.**

An appropriate strategy for studies of Mars's potential for life is to focus on the elements most relevant to life, especially carbon. This will require a determination of whether organic molecules are present on Mars and where, and of the chemical characteristics that will distinguish between meteoritic (nonbiological), prebiotic, and biological organic molecules. In addition, there is still much to be learned about the history and availability of water, and thus NASA should not abandon its current strategy of "following the water."

Finding. **The very successful intellectual approach of "follow the water" should be expanded to include "follow the carbon," along with other key biologically relevant elements.**

Any search for possible organic molecules within martian soil or rock samples must be undertaken in such a way as to avoid contamination by similar materials inadvertently transported from Earth. Similarly, life-detection experiments must avoid false-positive results caused by microbes inadvertently transported from Earth. Obtaining the desired science results demands that the contamination issues be addressed by appropriate planetary protection approaches. But it would be a mistake to not develop, because of concerns over planetary protection, appropriate procedures (e.g., new techniques for spacecraft cleaning and bioload reduction) that would allow access to the most promising sites for scientific discovery.

Finding. **The desire to visit and sample the highest-priority astrobiological sites requires that future surface missions to Mars take the necessary and appropriate planetary protection measures.**

Useful science analysis of martian surface samples can be carried out either in situ on the martian surface or in terrestrial laboratories with samples returned to Earth. Although in situ missions have many advantages, sample return offers the opportunity to carry out many more analyses on a sample than can be done in situ, to follow up exciting measurements with additional measurements that had not previously been anticipated, and to make measurements or observations using instruments that are not amenable to being accommodated on a lander or rover mission or that were not available at the time of mission development.

Finding. **The greatest advance in understanding Mars, from both an astrobiology and a more general scientific perspective, will come about from laboratory studies conducted on samples of Mars returned to Earth.**

Current astrobiology science goals for the exploration of Mars can be addressed via a series of robotic spacecraft missions in the near- to mid-term future. It is critical that any astrobiological evidence that might be present on Mars not be compromised by robotic or human activities before definitive measurements or sample return occur.

Finding. **The scientific study of Mars, including return to Earth of astrobiologically valuable samples that can be used to address the questions being asked today, can be done with robotic missions.**

CHARACTERISTICS OF POTENTIAL TARGET SITES

What are the characteristics of potential targets for Mars exploration that are particularly suited for elucidating the prebiotic and possibly biotic (and postbiotic) history of Mars, and what methods can be used to identify these targets? Current understanding of the interplay between organisms and their geological and planetary environment is strongly influenced by terrestrial experience. As such, the most relevant martian environments to investigate and the types of individual materials at those sites that should be studied are those with past or present associations with liquid water and having the potential to retain organic carbon.

Recommendation. **Sites that NASA should target with highest priority to advance astrobiology science objectives are those places where liquid water might exist today or might have existed in the past and where organic carbon might be present or might have been preserved.**

Sites pertinent to present-day or geologically recent water include the following:

- The surface, interior, and margins of the polar caps;
- Cold, warm, or hot springs or underground hydrothermal systems; and
- Source or outflow regions associated with near-surface aquifers that might be responsible for the "gullies" that have been observed.

Sites pertinent to geologically ancient water include the following:

- Source or outflow regions for the catastrophic flood channels;
- Ancient highlands that formed at a time when surface water might have been widespread (e.g., in the Noachian); and
- Deposits of minerals that are associated with surface or subsurface water or with ancient hydrothermal systems or cold, warm, or hot springs.

Although new measurements are likely to include major discoveries relevant to the identification of specific sites of relevance to astrobiology, a foundation of data is already available to identify exciting and appropriate sites for either in situ analysis or sample return.

Finding. **Identification of appropriate landing sites for detailed analysis (whether in situ or by sample return) can be done with the data sets now available or imminently available from currently active missions.**

Many of the types of sites listed above as being important for in situ investigation pertinent to ancient or recent life are not confined to the low latitudes and/or low altitudes accessible with current entry, descent, and landing technologies. Rather, many important sites are at high elevations or at polar latitudes. These include most of the ancient Noachian terrain that would tell researchers about the potential earliest life and polar regions where melting of ice (e.g., at relatively recent epochs of high obliquity) could provide liquid water to sustain life. Past and present Mars landers and rovers have not been able to access such sites because of technological limitations associated with their power supplies (e.g., sites in the polar regions) and entry, descent, and landing systems (e.g., sites at high altitudes). Technical advances are required if the most astrobiologically promising sites are to be accessible to future missions. Additional development of entry, descent, and landing technologies is, for example, especially important to enable landing within a readily traversable distance of a given point on Mars (e.g., to access small, high-value sites—such as hydrothermal vents—or to retrieve cached samples) or if high-mass payloads are to land at technically challenging sites, such as those at high elevation.

Recommendation. **Future surface missions must have the capability to visit most of the martian surface, including Noachian terrains and polar and high-latitude areas, and to access the subsurface.**

Exposure to strongly oxidizing environments or to high fluxes of radiation is not conducive to the preservation of biologically diagnostic carbon compounds. Earth-based experience suggests that the rock types best able to preserve biosignatures include fine-grained sedimentary rocks, evaporites, and hydrothermal deposits.

Recommendation. **Selection of samples for analysis (either in situ or of samples returned from Mars to Earth) should emphasize those having the best chance of retaining biosignatures.**

BIOSIGNATURES

What biosignatures reflect fundamental and universal characteristics of life? Unfortunately, there is no single comprehensive or unique biosignature whose presence would indicate life and whose absence would uniquely indicate the absence of life. Experience from studies of the martian meteorite ALH 84001 and analysis of evidence relating to claims of the earliest life on Earth have demonstrated that the potential interplay between putative organisms and their geological environment is so complex that researchers may never be able to identify a unique biosignature that would work in all environments and at all times. Rather, the sum total of all measurements on a sample, in the context of understanding of the origin and evolution of the martian environment, will be required.

Complicating the committee's task was the specific injunction in the charge that the discussion of biosignatures not be limited by an Earth-centric perspective. As a result, the committee made some specific assumptions about the likely characteristics of martian life forms. These assumptions are as follows:

- They are based on carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and the bio-essential metals.
- They require water.
- They exist as self-contained cell-like entities.
- They have sizes, shapes, and gross metabolic characteristics of organisms found on Earth.
- They employ complex organic molecules in biochemical roles.

The last assumption is particularly important because it implies that martian organisms will produce and use a wide range of small molecules and organic polymers that can serve as chemical biosignatures in their intact or fragmentary states. Experience with studies of terrestrial materials suggests that of all the various life-detection techniques available, analysis of carbon chemistry is the first among equals. In other words, organic analysis is likely to provide a more robust way to detect life than imaging technologies, mineral assemblages, isotopic measurements, or any one other single technique. This is the case because, on Earth, the patterns of biogenic carbon compounds reflect organized polymerization of smaller subunits, or precursors, and comprise mixtures with a limited range of atomic spatial arrangements very different from those made by abiological processes. However, organic analysis alone is insufficient to detect life. An ensemble of all of the relevant methodologies, combined with analysis of geological and environmental plausibility, will likely provide the best evidence for the presence or absence of life in a sample.

Recommendation. **The lack of a comprehensive understanding of all of the potential biosignatures for Mars exploration means that NASA should employ a combination of techniques that utilize both Earth-centric and non-Earth-centric approaches that focus on the basic concepts in carbon chemistry, imaging, mineral assemblages, and isotopic measurements.**

Specific aspects of carbon chemistry that should be investigated include the following:

- The presence of polymers based on repeating universal subunits;
- Patterns in the carbon isotopic compositions of organic molecules that reflect organized polymerization of smaller subunits or precursors;
- Patterns in the carbon numbers of organic compounds; and
- The presence of carbon compounds that have only a subset of the possible connectivities or atomic spatial arrangements (i.e., just a few structural isomers or stereoisomers and/or strong chiral preferences).

EXPLORATION METHODOLOGIES AND INSTRUMENTATION

What research activities would improve exploration methodology and instrumentation capabilities to enhance the chances of astrobiological discovery? Currently operating and planned Mars missions all are, or will be, returning scientific data that directly address astrobiology goals in substantive ways. Thus, if astrobiologists are to advance their science goals for the exploration of Mars, they must work with NASA to ensure that the upcoming missions proceed as scheduled, and then take advantage of the scientific data these spacecraft will collect. Ensuring the success of future missions will require attention to the following activities:

- Technology development,
- Research and analysis activities, and
- Supporting activities such as studies of martian meteorites and Mars-analog environments on Earth.

Future Mars missions will require significant technical advances if they are to be carried out successfully. Technology development must occur both in mission-related areas (e.g., entry, descent, and landing systems, including a precision landing capability; sample-return technology; in situ sample processing and handling; and planetary protection) and in astrobiological science instrumentation development (so that the necessary next generation of instruments is ready to go).

Recommendation. **The Mars Exploration Program must make stronger investments in technology development than it does currently.**

Research and analysis (R&A) programs are the mechanism by which scientific results are extracted from the data returned by current missions and by which concepts for future missions are developed. R&A programs are the primary vehicle by which the Mars Exploration Program can maintain its vitality in response to new discoveries, and such programs represent a vital investment in nurturing the next generation of space scientists, engineers, and program managers.

Recommendation. **Continued strong support of NASA's basic research and snalysis programs is an essential investment in the long-term health of the Mars Exploration Program.**

Analysis of martian meteorites has been central to the development of the current understanding of Mars, its potential for life, and the development of current ideas about detection of present or fossil life. It is especially important to search for martian meteorites that formed during early periods of Mars's history, as well as meteorites of sedimentary origin. This is an important area of collaboration between NASA and the National Science Foundation.

Recommendation. **Collection and analysis of martian meteorites must continue, even though biases in the compositions and ages of these meteorites, their uncertain provenance, and the effects of impact-ejection and transfer to Earth mean that they cannot take the place of samples returned from Mars.**

As with the analysis of martian meteorites, studies of Mars-analog sites on Earth are essential to mission development and execution and to the training of the scientists, engineers, and managers engaged.

Recommendation. **Terrestrial analog studies should include testing instrumentation, developing techniques for measuring biosignatures under Mars-like conditions, and conducting technological proof-of-concept studies.**

MAXIMIZATION OF SCIENCE

What approaches to the exploration of Mars will maximize the astrobiological science return? The astrobiology science goals for Mars are extremely broad, and it can be argued that virtually any mission can return data of relevance to issues relating to the habitability of Mars. However, consideration of the data from past and current Mars missions and expectations for those currently in development for launch during the 2007 and 2009 opportunities suggest that the greatest increase in understanding of Mars will come from the collection and return to Earth of a well-chosen suite of martian surface materials. Given the Mars Exploration Rover experience and current understanding of the nature of materials on the martian surface, a "grab sample" obtained from a stationary lander is not likely to be sufficient to provide the necessary data.

Finding. **Sample return should be seen as a program that NASA and the Mars science community have already embarked upon rather than as a single, highly complex, costly, and risky mission that is to occur at some future time.**

Recommendation. **The highest-priority science objective for Mars exploration must be the analysis of a diverse suite of appropriate samples returned from carefully selected regions on Mars.**

Programmatically, sample return should be phased over three or more launch opportunities. That is, samples can be collected and cached on Mars by one or more missions. A selected cache can be retrieved by a subsequent mission and launched into orbit about Mars for collection and return to Earth at a later date. Sample caching could be carried out by each surface mission, utilizing a minimalist approach so as not to make sample caching a cost- or technology-driver. Such a strategy, accompanied by a reduction in the size of the landing error ellipse, should allow collection of diverse samples and mitigate the costs of sample-return missions.

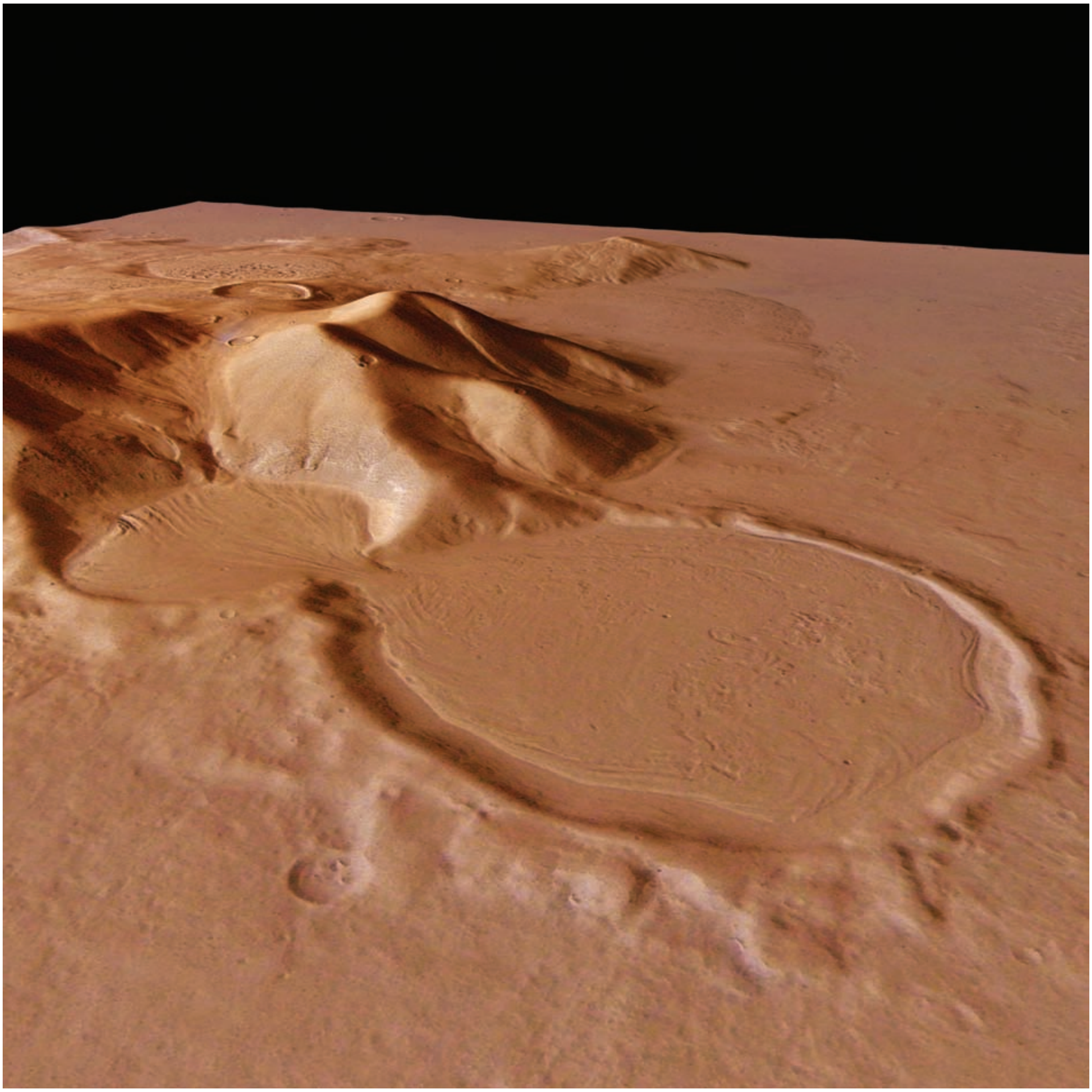
Irrespective of the compelling scientific arguments for the return of martian samples to Earth, the implementation of a sample-return mission will be a technically challenging, high-risk, high-cost endeavor. Because it will be comparable in expense to the highest-priority activities proposed by other scientific communities, the decision to implement a Mars sample-return mission will hinge on factors beyond the scope of this study. As such, it behooves the astrobiology community to plan for the possibility that a Mars sample-return mission is not an integral component of current mission plans.

Recommendation. **If it is not feasible to proceed directly toward sample return, then a more gradual approach should be implemented that involves sample caching on all surface missions that follow the Mars Science Laboratory, in a way that would prepare for a relatively early return of samples to Earth.**

If a commitment is not made for sample return, then high-priority, astrobiologically relevant science still can be done on Mars with missions such as the Astrobiology Field Laboratory or the Mid Rovers, provided that they are instrumented appropriately. However, it must be recognized that the ability of these missions to make fundamental discoveries is much more limited than would be the case with a sample-return mission.

International collaboration has the potential to make expensive undertakings such as a Mars sample-return mission affordable. But the benefit has to be balanced against the political difficulties of working with multiple countries and multiple space agencies.

Recommendation. **International collaboration in Mars missions should be pursued in order to make expensive missions affordable, especially in the areas of sample caching and sample return.**



1

Introduction

The resurgence in scientific interest in the potential for life on Mars began in the 1990s. It was recognized at that time that the types of extreme environments on Earth capable of supporting organisms, such as geothermal systems, hot springs, subfreezing environments, and the deep subsurface, likely existed on Mars and had the potential to support life there.[1] The possibility of martian life gained visibility with both the science community and the public with the hypothesis of McKay et al. that evidence for past life could be found in the martian meteorite ALH 84001.[2] Although that hypothesis has now been widely criticized, the ensuing discussion brought out the scientific value of incorporating astrobiology science goals into a broad exploration strategy for Mars.

In the late 1990s, the NASA Mars Exploration Program plan emphasized the study of Mars as an integrated system. The potential for life, the history of the climate, and the geological and geophysical evolution of the planet were recognized as all relating to the abundance, behavior, and history of water as the common intellectual thread. The strength of this approach was the ability to utilize cross-disciplinary information to address a common set of scientific questions. Although each of the major topics was considered important on its own, the questions about life were considered to be "more equal among equals." The astrobiology goals were given central importance as a scientific driver for much of the space exploration program,[3] and funding available for the Mars Exploration Program in particular was augmented in response to its enhanced emphasis on "life" questions.

Reflecting this emphasis, the Mars Exploration Program Analysis Group (MEPAG) defined the scientific goals and objectives for exploring Mars. Scientific goals were grouped according to their emphasis on life, climate, geology, and preparation for human missions. Although the goals were not prioritized across these categories, they did reflect the emergence, if not preeminence, of life-related questions. The initial goals and objectives[4] have been updated several times, with the current version responding to measurements and discoveries made by the most recent round of spacecraft missions.[5]

The Vision for Space Exploration announced by President George W. Bush in February 2004 also emphasized astrobiology questions as being at the center of the program. The goals for exploration of the solar system put

FIGURE 1.1 Glaciers on Mars. Ice-rich material seems to have flowed from the smaller crater nestled against the mountain into the lower, larger crater at the base. The craters, which are located at the eastern edge of Hellas Basin, contain the traces of glaciers. The smaller crater is 9 km across, and the larger crater is 16 km across. Image courtesy of ESA/DLR/FU Berlin (G. Neukum).

forward by NASA in response to the Vision focused on astrobiology. For Mars, the objective was to "[c]onduct robotic exploration of Mars to search for evidence of life, to understand the history of the solar system, and to prepare for future human exploration," and the goals across the solar system all had astrobiology objectives at their center.[6] Irrespective of the central roles that astrobiology, in general, and the search for life on Mars, in particular, appear to play in NASA's enunciated goals, budgetary decisions made in 2006 seemed to undercut this commitment.[7] Fortunately, events in 2007 suggest that the downward trend in NASA's astrobiology spending may have been reversed.

At approximately the same time as these policies were being developed, the National Research Council's (NRC's) decadal survey for solar system exploration emphasized that astrobiology goals, related to understanding the habitability of the planets and satellites and determining the distribution of life in our solar system, should be considered central to the underlying rationale for solar system exploration.[8] The missions identified by the decadal survey as addressing high-priority science goals, although not identified as astrobiology missions per se, all addressed key astrobiology goals.

The closest preceding document related to a Mars astrobiology strategy was the 1995 NASA report titled *An Exobiological Strategy for Mars Exploration*.[9] That report laid out the scientific objectives for martian astrobiology and identified the then-key points for implementing a successful astrobiology strategy. The basic approach outlined in that document was to carry out the exploration of Mars in discrete phases, each providing an increasingly detailed look at the planet. The phases described were the following:

1. Global reconnaissance in order to understand global processes and to identify sites for detailed in situ investigations;
2. Exploration of particular sites in detail using landed packages in order to understand their geology and history;
3. Deployment of astrobiologically relevant instruments onto the surface that focus on prebiotic chemistry, past life, and/or present life;
4. Robotic return of samples of the surface back to Earth for detailed analysis; and
5. Human exploration of the martian surface.

Remarkably, the Mars Exploration Program as actually implemented in the last decade closely follows the first three exploration phases recommended in the 1995 NASA report. Global reconnaissance has been carried out by Mars Global Surveyor, Mars Odyssey, and, now, Mars Reconnaissance Orbiter. The combination of high-resolution imaging; multispectral mapping in the visible, near-infrared, and thermal infrared; compositional mapping using gamma-ray and neutron techniques; and radar mapping of the subsurface has provided detailed information on the geological history of Mars and on processes that pertain to the potential for liquid water and for life. In situ analysis by the Mars Exploration Rovers *Spirit* and *Opportunity* investigated two sites for which there was evidence for significant water-related activity and confirmed that liquid water played an important role at both. Two missions planned for the rest of this decade, the 2007 Phoenix lander that will investigate the geology and chemistry of high-latitude ground ice and the 2009 Mars Science Laboratory that will investigate astrobiologically relevant chemistry and climate behavior, are both missions that address fundamental astrobiology science objectives.

It is in this context that the present scientific strategy for the astrobiological exploration of Mars has been formulated. Although the science issues had been discussed previously as components of prior NRC reports,[10–12] this is the first time that an integrated astrobiology strategy has been constructed for Mars by the NRC. The construction of such a strategy recognizes the increased scientific importance of astrobiology, and of astrobiology for Mars in particular, within the overall space science community. Not only does Mars arguably have the best chance in the solar system (other than Earth) of having or having had life, but it is also the most accessible of the bodies that are important to the astrobiological study of the solar system.

All of these considerations have informed the committee's effort to describe the science objectives for the subsequent astrobiological investigation of Mars. Although science objectives are emphasized in the committee's strategy, they cannot be developed in isolation from knowledge of what instruments are or might be available to make measurements, how they can be assembled into flight missions, and what the costs are relative to the amounts of funding likely to be available.

OUTLINE OF APPROACH

In developing a strategy, the committee followed some general guidelines given in previous reports and scientific discussions that include consideration of the following:

- The breadth of astrobiology goals,
- Lessons learned from past searches for life, and
- The biochemical nature of life.

The Breadth of Astrobiology Goals

The committee's general approach is that astrobiology goals are broader than determining whether life is (or has been) present or is absent. Although such a determination is a key goal for the astrobiological study of Mars, a proper understanding of the significance of the findings is broader. By understanding the nature of habitable environments and the history of habitability (Box 1.1) on Mars and how they differ from Earth's, as well as the nature of the relationship between organisms and their planetary environment and how those relationships might differ between planets, researchers can apply the results to estimates of where life might exist in our solar system other than on Mars and what the distribution of life on extrasolar planets and throughout the galaxy might be. Furthermore, having the broader astrobiological context might be necessary to determine whether, in fact, life is present or absent.

Indeed, it is entirely possible that life never existed on Mars. A definitive conclusion, if such were possible, that Mars is, was, and always has been lifeless would not represent an astrobiological failure. Rather, such a finding would be just as important scientifically as a finding of life, in terms of constraining our views on the origin, evolution, and distribution of living organisms in the universe.

Lessons Learned from Past Searches for Life

The committee assumes, based on experience garnered from previous searches for martian life associated with the Viking mission in the 1970s and analysis of the martian meteorite ALH 84001 in the 1990s and 2000s, that a single mission will not necessarily be able to determine if martian life is or ever was present and to characterize the boundary conditions of martian habitability. Thus, the committee anticipates that a progression of missions will be required that have the following characteristics:

- The missions will span the range of issues related to the habitability of Mars, the potential for martian life, and whether life actually is present; and
- The missions will allow for a sufficiently detailed look at the organic geochemistry of Mars that scientists can actually determine whether life is present or absent and, if the former proves to be the case, investigate its characteristics.

The committee recognizes that habitability and the actual occurrence (or not) of life are inextricably linked.

The Biochemical Nature of Life

The committee's charge explicitly asked that it address searching for life that might not be Earth-like, and the NRC report *The Limits of Organic Life in Planetary Systems* provides a convenient starting point for such a discussion.[13] That report was prepared to examine the possibilities for unconventional forms of life and to address, in part, concerns that previous life-detection experiments had not considered the wider possibilities for life (i.e.,

BOX 1.1
The Concept of Habitability

In its strategy, the committee makes extensive use of the concept of habitability, as does the Mars science community as a whole. MEPAG has defined habitability as:[1]

> A general term referring to the potential of an environment (past or present) to support life of any kind. In the context of planetary exploration, two further concepts are important: *Indigenous habitability* is the potential of a planetary environment to support life that originated on that planet, and *exogenous habitability* is the potential of a planetary environment to support life that originated on another planet.

In general, the concept of habitability does not relate to whether life actually exists or has existed on a planet. It refers instead to whether environmental conditions are such that life could exist, grow, and multiply, and whether resources are available that can support life. Such environmental conditions are discussed in Chapter 4 but might include, for example, temperatures between about 253 K and 304 K, a range in which liquid water can exist and life can function; salinity or pH within ranges in which life can exist; and the actual presence of liquid water. Although life can exist in a frozen, dormant state at liquid nitrogen temperatures, it can neither grow nor multiply, so that an environment at that temperature would not qualify as habitable. The concept of habitability is difficult to apply in that researchers have only terran life as a guide, and the range of conditions in which life in general could conceivably function is likely to be broader than the range in which terran life functions, but by an unknown degree; thus, the concept of habitability includes a theoretical component and has a significant degree of uncertainty.

Related to habitability is the concept of a habitat. As used in this report, the term “habitat” refers to an environment (defined in time and space) that is or was occupied by life.[2] Although habitability and the occupation of a habitat by life are general concepts, the committee uses them more specifically to mean habitability by microbial organisms.

The question What is life? cannot be addressed easily by definitions. The reader is referred to discussions of this question in Box 1.2.

---

[1]A. Steele, D.W. Beaty, J. Amend, R. Anderson, L. Beegle, L. Benning, J. Bhattacharya, D. Blake, W. Brinckerhoff, J. Biddle, S. Cady, P. Conrad, J. Lindsay, R. Mancinelli, G. Mungas, J. Mustard, K. Oxnevad, J. Toporski, and H. Waite, “The Astrobiology Field Laboratory,” Unpublished white paper, 72 p, posted December 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

[2]See, for example, Steele et al., “The Astrobiology Field Laboratory,” December 2005.

what the *Limits* report calls nonterran life) and had been too geocentric in concept and execution. The reader is referred to that report for an extended discussion of possibilities for nonterran life. The generic characteristics of life as we know it—terran life, in the terminology of the *Limits* report—can be summarized as the following:

- Uses water as a solvent;
- Is built from cells, and exploits a metabolism that focuses on the C=O carbonyl group;
- Is a thermodynamically dissipative structure exploiting chemical energy gradients; and
- Exploits a two-biopolymer architecture that uses nucleic acids to perform most genetic functions, and proteins to perform most catalytic functions.

What complicates the discussion is the fact that martian life might be terran or nonterran. If some variant of

BOX 1.2
What Is Life?

Any discussion of the environmental requirements necessary to support life or of the search for life on another planet begs the question, What is life? This is a difficult question to answer, and there is no wide agreement on a definition.[1] Sagan described a number of characteristics of life on Earth, including the ability to take in nutrients and produce waste products, the ability to grow and reproduce and to pass on genetic information, the ability to respond to the environment, and the ability to evolve via Darwinian evolution.[2] Each of these characteristics generally applies to life on Earth, but each has clear exceptions that preclude its use as a definition. Standard counterexamples include fire, which takes in nutrients and produces waste products and grows, and mules, which are incapable of reproducing or evolving via Darwinian evolution. Although researchers think that entities that meet most or all of Sagan's criteria are alive, and that those that meet few are not alive, this set of requirements has been carefully tuned to human preconceptions of what is or is not alive.[3]

Cleland and Chyba have argued that it is not possible to arrive at a unique definition for life without first having a comprehensive theory of life. This situation is analogous to the difficulty of defining water without first having a comprehensive molecular theory that tells us that water consists of H_2O.[4]

Efforts to define life may be subject to the kind of ongoing controversy associated with efforts to define a planet (in the context of asking whether Pluto is a planet or not). Planets, in fact, represent a subset of objects generally associated with stars, and for which there is a smooth continuum of characteristics that include size, composition, and location in their planetary system, as well as the discrete characteristic of whether they orbit another object that itself orbits the star. It may not be possible to define a unique boundary between planets and nonplanets with which all scientists would agree. Similarly, the boundary between living and nonliving may be gradational, and it may not be possible to draw a unique dividing line. Defining life may have similar problems.

This lack of a concrete definition does not preclude the study of life in the universe or efforts to detect it on other planets. Rather, the questions that it raises and how they are answered will provide us with a much better understanding of our own existence here on Earth.

---

[1]See, for example, C.F. Chyba and K.P. Hand, "Astrobiology: The Study of the Living Universe," *Annual Reviews of Astronomy and Astrophysics* 43:31-74, 2005; and references therein.

[2]C. Sagan, "Life," in *Encyclopedia Brittanica* 22:964-981, 1970.

[3]B. Jakosky, *Science, Society, and the Search for Life in the Universe*, University of Arizona Press, Tucson, 2006.

[4]C.E. Cleland and C.F. Chyba, "Does 'Life' Have a Definition?" in W. Sullivan and J. Baross, eds., *Planets and Life: The Emerging Science of Astrobiology*, Cambridge University Press, Cambridge, U.K., in press, 2007.

the Panspermia hypothesis is correct, life on Mars and on Earth might have a common origin, and so martian life would be terran by definition. But if life arose independently on Earth and on Mars, it can be argued that martian life would likely be nonterran because of the vanishingly small possibility that the same basic biochemical architecture would have evolved on two different planets. However, it could also be argued that the terran model is so compelling that its adoption is virtually guaranteed by the laws of physics and chemistry.[14] Without a general theory of the origin of life it is impossible to decide which, if any, of these arguments is likely to be correct. For more discussion, see Box 1.2.

Thus, the committee faced a dilemma. The simplifying assumption that martian life is terran was excluded because the committee was specifically asked to address a search for life that might be non-Earth-like in its characteristics. But scientists and science-fiction writers have been highly inventive in their speculations about the possibilities of "life as we don't know it."[15] A systematic discussion of all of the hypothetical nonterran life forms discussed in the scientific literature is beyond the scope of this study. Thus, to create a tractable problem, the committee made some specific assumptions about the likely characteristics that hypothetical martian life forms will display. These assumptions are as follows:

- They are based on carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and the bio-essential metals of terran life.
- They require water.
- They have structures reminiscent of terran microbes. That is, they exist in the form of self-contained, cell-like entities rather than as, say, a naked soup of genetic material or free-standing chemicals that allow an extended system (e.g., a pond or lake) to be considered a single living system.
- They have sizes, shapes and gross metabolic characteristics that are determined by the same physical, chemical, and thermodynamic factors that dictate the corresponding features of terran organisms. For example, metabolic processes based on the utilization of redox reactions seem highly plausible. But the details of the specific reactions, including the identities of electron donors and electron acceptors, will be driven by local conditions and may well not resemble those of their terran counterparts.
- They employ complex organic molecules in biochemical roles (e.g., structural compounds, catalysis and the preservation and transfer of genetic information) analogous to those of terran life, but the relevant molecules playing these roles are likely different from those in their terran counterparts.

These characteristics are based on generalizations of the characteristics of terran life that might be applicable to life found elsewhere in the universe. There are additional characteristics of life on Earth that must be carefully considered when searching for life on Mars lest they become too strong a guide and, as a result, bias the search. A prime example of such a bias is the fact that most life on Earth is powered either directly or indirectly by the Sun. Photosynthesis is not likely to be a major driver of hypothetical martian life because of the difficulties that organisms would have in surviving on or near the planet's surface.

Although each of these assumptions might conceivably be wrong, they represent a starting point and at the same time allowed the committee to have an initial basis of understanding about what will allow a search for non-Earth-like life and conditions. In the end, though, astrobiologists will be guided by what is actually found on Mars. Nonrandom groupings of elements, molecules, or larger structures will stand out in detailed analyses of surface materials; although they may not be interpreted as being indicative of life, they will point to issues requiring further study. Thus, in designing a strategy for Mars exploration, astrobiologists must start close to those things they currently understand about life and its context of the origin and evolution of planetary environments, but then retain sufficient flexibility to branch farther and farther afield as the data require.

REFERENCES

1. P.J. Boston, M.V. Ivanov, and C.P. McKay, "On the Possibility of Chemosynthetic Ecosystems in Subsurface Habitats on Mars," *Icarus* 95:300-308, 1992.

2. D.S. McKay, E.K. Gibson, Jr., K.L. Thomas-Keprt, H. Vali, C.S. Romanek, S.J. Clemett, X.D.F. Chillier, C.R. Maechling, and R.N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH 84001," *Science* 273:924-930, 1996.

3. National Aeronautics and Space Administration, *Astrobiology Roadmap: September 2003,* National Aeronautics and Space Administration, Washington, D.C., 2003.

4. MEPAG (Mars Exploration Program Analysis Group), "Scientific Goals, Objectives, Investigations, and Priorities," *Science Planning for Exploring Mars*, JPL Publication 01-7, 2001, available at http://mepag.jpl.nasa.gov/reports/index.html.

5. MEPAG, "Mars Scientific Goals, Objectives, Investigations, and Priorities: 2006," white paper, J. Grant, ed., 31 p., February 2006, available at http://mepag.jpl.nasa.gov/reports/index.html.

6. National Aeronautics and Space Administration, *The Vision for Space Exploration: February 2004,* National Aeronautics and Space Administration, Washington, D.C., 2004.

7. National Research Council, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, pp. 20-21.

8. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington, D.C., 2003.

9. National Aeronautics and Space Administration, *An Exobiology Strategy for Mars Exploration,* National Aeronautics and Space Administration, Washington, D.C., 1995.

10. See, for example, National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy,* The National Academies Press, Washington D.C., 2003.

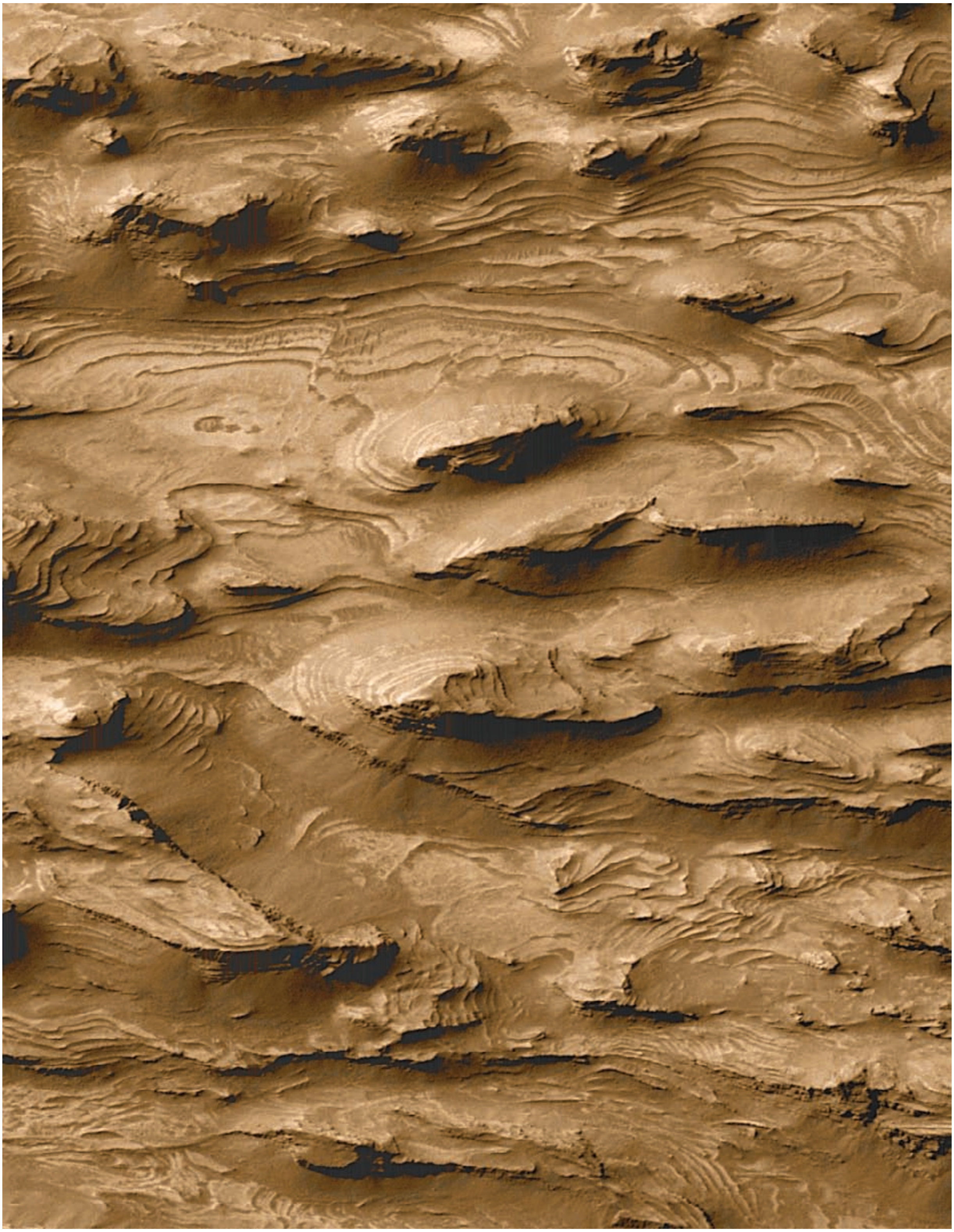
11. See, for example, National Research Council, *Assessment of Mars Science and Mission Priorities,* The National Academies Press, Washington D.C., 2001.

12. See, for example, National Research Council, *Assessment of NASA's Mars Architecture 2007-2016,* The National Academies Press, Washington D.C. 2006.

13. National Research Council, *Limits of Organic Life in Planetary Systems,* The National Academies Press, Washington D.C., 2007.

14. See, for example, N.R. Pace, "The Nature of Biochemistry in the Universe," and S.A. Benner, "Chance and Necessity in Biomolecular Chemistry: Is Life as We Know It Universal?" pp. 59-63 and 64-67 in National Research Council, *Signs of Life: A Report Based on the April 2000 Workshop on Life Detection Techniques*, The National Academies Press, Washington, D.C., 2002.

15. For a recent scientific discussion of some of the possibilities see, for example, D. Schulze-Makuch and L.N. Irwin, *Life in the Universe: Expectations and Constraints*, Springer, New York, 2004.



2

The Present State of Knowledge About Mars and Possible Life

ENVIRONMENTAL REQUIREMENTS FOR LIFE

Life requires energy sources, the nutrients necessary for building structures and synthesizing catalysts, and access to environments in which biosynthesis and maintenance of biostructures are possible. Potential energy sources for life on Mars include the direct and indirect utilization of solar radiation, lightning, ionizing radiation, geothermal heat, and various redox couples involving carbon or inorganic compounds. As discussed by Price and Sowers,[1] the energy requirements for survival are likely a million times less than the energy required for growth. The concept of survival energy, that which is required for repair of macromolecules, maintenance of ion gradients, and so on,[2] implies that life could survive, although not multiply, in a much wider range of environments than was formerly thought possible.

The availability of nutrient elements may also impose limits to life. As mentioned in Chapter 1, it is reasonable to assume that martian life, if any, would be based on carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S). Mars was built from the same carbonaceous chondritic material as Earth. The same elements would accordingly be available to be utilized by life on Mars as on Earth unless processes on Mars caused their depletion. C, H, N, O, P, and S have all been detected on Mars. But the amount of nitrogen is a potential problem.[3] The martian atmosphere contains only 160 microbars (mbar) of N_2, and nitrates have not been detected in the soils. Much of the original nitrogen inventory could have been lost by impact erosion of the atmosphere during heavy bombardment, subsequent sputtering by the solar wind, or photochemical processes. Access to organic carbon is another potential problem. While CO_2 is the dominant species in the atmosphere, reduced carbon compounds may be rare at the surface, despite continual delivery of organic compounds to the martian surface in meteorites and interplanetary dust particles. Nevertheless, reduced carbon compounds have been detected in the martian meteorite ALH 84001. There is little reason to assume that the availability of other elements on Mars is significantly different from their availability on Earth.

Since no martian life has been detected, it is not possible to determine what its environmental requirements are. However, current understanding of the limits of terran life continue to expand as living forms are found in

FIGURE 2.1 The layers in Candor Chasma mimic those created by sedimentation in underwater environments on Earth. This image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft is courtesy of NASA/JPL/Malin Space Science Systems. The image covers an area of 1.5 by 2.9 km.

ever greater extremes of temperature, pressure, pH, salinity, and so forth.[4] One environmental factor that is almost universally accepted as necessary for life is at least episodic access to liquid water. This observation has implications for temperature but does not necessarily imply temperatures between 273 K and 373 K. Although there is theoretical evidence that metabolism can continue at temperatures at or below 233 K, there is no evidence of active cells below 253 K and no direct observation of cell replication below 248 K.[5,6] At the high-temperature end, life has been cultured in the laboratory at 394 K,[7] although evidence from deep-sea hydrothermal vents indicates that the upper temperature limit for life may be much higher than this.[8] Apart from temperature, two other parameters critical to the survival of terran life are worthy of note—water activity and radiation resistance. The availability of liquid water to an organism is critical for its survival. Many organisms are resistant to desiccation; however, currently no organisms are known to survive at water activities lower than $a_W = 0.61$.[9] Therefore, temperature and water activity have recently been used to constrain regions on Mars associated with special planetary protection considerations.[10]

DOES MARS MEET HABITABILITY REQUIREMENTS?

The following discussion focuses on the availability of water. The committee assumes that solar energy, geothermal energy, and chemical energy, as well as nutrients, are available on Mars. Sources of energy and nutrients are present on Mars as they would be on any geologically active planet, although questions about the availability of nitrogen have not been resolved.[11] A major unknown is where and when liquid water was available to enable the assets present to be used for a possible origin or maintenance of life.

Present Environmental Conditions

Conditions on the surface of Mars today are very inhospitable for life, but geological evidence suggests that conditions were more hospitable in the past, particularly the distant past. Liquid water is believed to be essential for life. With mean annual surface temperatures close to 215 K at the equator and 160 K at the poles, the ground is frozen on average to a depth of several kilometers to form a thick cryosphere. Any water present in this zone would be frozen. The cryosphere might be thinner locally in areas of anomalously high heat flow, but no such areas have been identified. The atmosphere is thin, with an average surface pressure of 5.6 mbar, and composed largely of CO_2. Because the atmosphere is so thin, the Sun's ultraviolet radiation passes almost unattenuated through it to the surface. Surface temperatures fluctuate widely during the day. On a clear summer day they may exceed 273 K close to noon. However, the fluctuations damp out rapidly at depth to converge on the average daily temperature, which is everywhere well below freezing, so that temperatures above freezing are restricted to the upper few centimeters. The ground is permanently frozen down to a kilometer or so below these depths.

Under present conditions, and probably under conditions that have prevailed for the last few billion years, weathering rates have been extremely low. Rocks in the Gusev crater have a millimeter-thick, oxidized rind, rich in volatiles such as sulfur, chlorine, and bromine.[12,13] Soils have highly variable volatile contents and may contain an oxidizing agent. The fraction of organics in the soil is unknown. Although it was anticipated that the Viking gas chromatograph-mass spectrometer would detect some complex organic compounds, none were detected at the parts per billion level, and the Mars Pathfinder APXS measurements of soil could not detect carbon. The nitrogen content of the soils is also unknown.

Both poles have a residual water ice cap that is exposed when the CO_2 cap recedes in the summer (see Figures 3.1 and 6.1), although in the south only small areas are exposed even at midsummer.[14] Because of the cold polar temperatures, only minute amounts of water vapor are present in the atmosphere.[15] Observations of seasonal frost and water fog in some areas on Mars demonstrate that the water content of the atmosphere varies both spatially and seasonally. However, if all the water vapor were precipitated out, it would form a global layer only about 10 μm thick. Abundant ground ice, however, may be present and available to interact with the atmosphere, and to enhance its water content should conditions change.[16] Under present conditions, at depths greater than a few tens of centimeters below the surface at latitudes in excess of 50° north and south, water ice is stable. Consistent with these conditions, large fractions of ice have been detected just below the surface at these latitudes by orbital gamma-ray and neutron spectroscopy.[17] At lower latitudes ground ice is unstable at all depths because temperatures exceed the 200 K frost-point temperature. The cause of the several percent water detected at these low latitudes is still being debated. It could be mineralogically bound water or ice inherited from an earlier era when stability relationships were different.

Parts of the surface are at elevations where the atmospheric pressure exceeds 6.1 mbar, the pressure at the triple point of water. At most locations, heating of ice-containing soils or surface frosts would result in sublimation without the intervening liquid phase, but where the pressure is in excess of the triple point, liquid could form transiently. Because of the low diurnal mean temperature, any such liquid would be very short lived. It would rapidly freeze and sublimate.

Although the present-day average climate is not conducive to the occurrence of liquid water, the possibility exists that liquid water can occur at the surface as a transient phase. Gullies appear to have released water to the surface, for example, and recent observations (Figure 2.2) suggest that this is happening in the present epoch (i.e., within the last 5 years or so).[18] Similarly, transient melting of snow also can occur under very specific conditions.[19] While the ramifications of transient liquid water are very different from those for a steady-state occurrence of liquid water, both have potential implications for possible life.

In the recent geological past, stability relationships may have been somewhat different. Mars undergoes large changes in its obliquity (i.e., the tilt of its polar axis).[20] At present the obliquity ranges from 23 to 27° about a mean of 25°, but during the last 10 million years obliquities have been at least as high as 46°. At higher obliquities, the water content of the atmosphere is likely higher, ground ice is stable closer to the equator, and surface ice may be transferred from the poles to lower latitudes. In addition, during the summer at high latitudes, pole-facing slopes are continually illuminated by the Sun. One possibility for the formation of young gullies (see Figures 2.7 and 8.1) on steep, pole-facing slopes is that they form during periods of high obliquity as a result of liquid water produced during the summer by melting of snow that accumulated on the slopes during the long cold winter.[21] High obliquities may also be implicated in the formation of some of the younger valley networks.

On present-day Mars, the subsurface may be more hospitable to life than the cold, oxidizing surface with its high ultraviolet (UV)-radiation fluxes. As indicated above, the cryosphere is on average several kilometers thick, and liquid water is unlikely within kilometers of the surface. However, the young crystallization ages of most martian meteorites[22] and the apparent youthfulness of some volcanic features suggest that Mars today is volcanically active, at least intermittently. Heat flow under volcanic regions such as Tharsis may be significantly larger than the average, and the cryosphere correspondingly thinner. Moreover, given the presence of extensive ground ice, hydrothermal activity is likely in volcanically active areas, although none has been detected, and such activity (or even the background geothermal heat flux) could drive water to the surface.

In summary, present conditions at the surface of Mars are inhospitable to life, mainly because of the high UV flux, the presence of oxidants, and the scarcity of organic compounds, and because the low temperatures inhibit the presence of liquid water. However, liquid water may exist near the surface transiently in anomalous situations, ground water may be present at shallow depths in areas of anomalously high heat flow, and hydrothermal systems may be present in volcanic regions. Furthermore, at depths below a couple of kilometers, temperatures will be warm enough to allow liquid water in the pore space in rock, such that a deep-subsurface biosphere is possible, provided that appropriate nutrients are accessible and water can circulate.

Past Environmental Conditions

Noachian

Conditions in the geological past, particularly the distant past, were likely, at least at times, to have been very different from present-day conditions. The best evidence for different conditions is for the Noachian, the period of heavy meteorite bombardment that ended around 3.8 billion years ago (Box 2.1). Most surfaces that date from this era are heavily dissected by networks of valleys a few kilometers wide but up to a few thousand kilometers long. Relatively high drainage densities suggest surface runoff that would require either rainfall or melting snow, which in turn implies significantly warmer and wetter conditions than those that prevail today (Figure 2.3). The

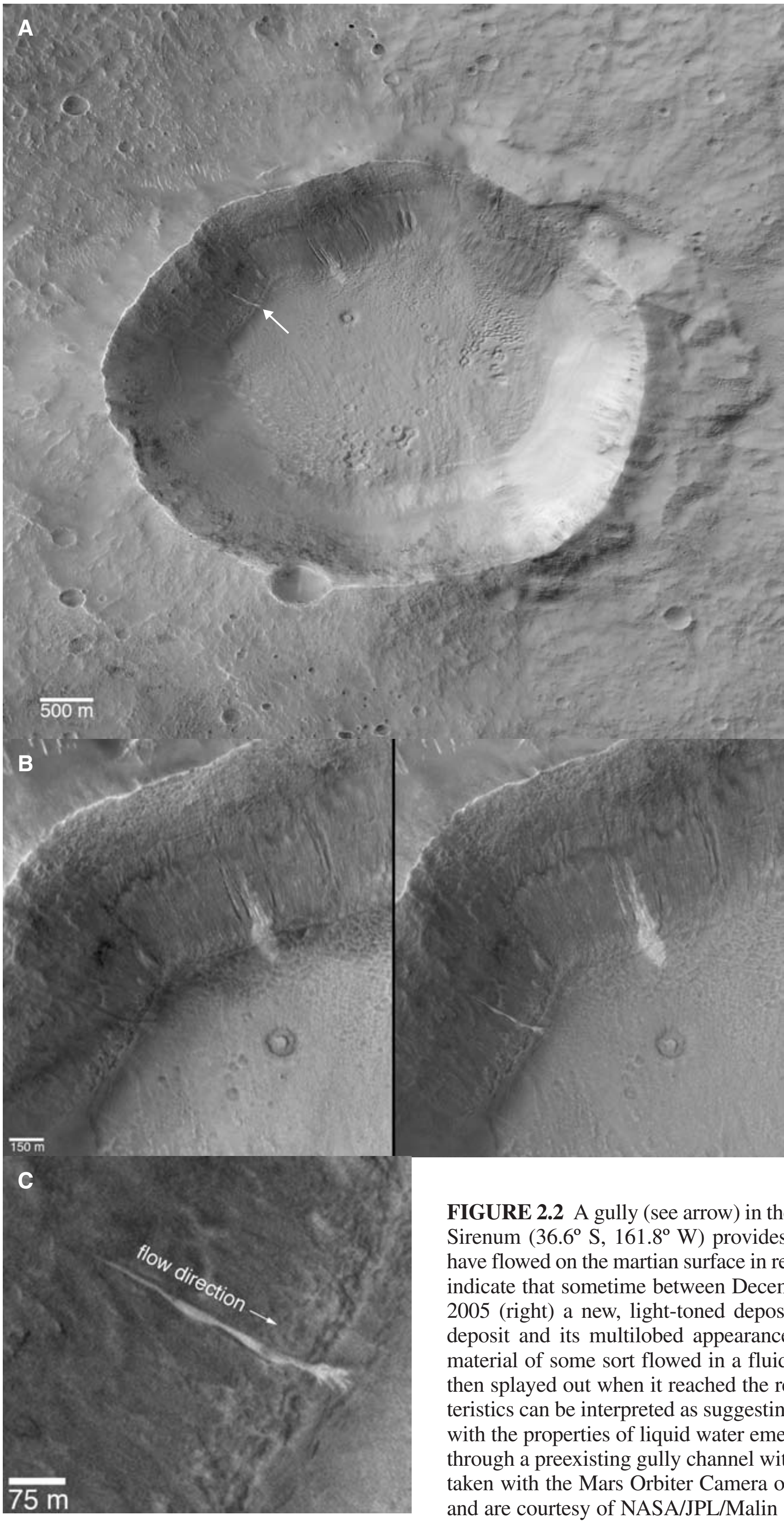


FIGURE 2.2 A gully (see arrow) in the wall of an unnamed crater (A) in Terra Sirenum (36.6º S, 161.8º W) provides tantalizing evidence that water might have flowed on the martian surface in recent times. Close-up images (B) clearly indicate that sometime between December 2001 (left) and August/September 2005 (right) a new, light-toned deposit filled the gully. The thinness of the deposit and its multilobed appearance at its downhill end (C) suggest that material of some sort flowed in a fluid-like manner down the crater wall and then splayed out when it reached the relatively flat crater floor. These characteristics can be interpreted as suggesting that a mixture of sediment and a fluid with the properties of liquid water emerged from the crater wall and ran down through a preexisting gully channel within the last 5 years. These images were taken with the Mars Orbiter Camera on the Mars Global Surveyor spacecraft and are courtesy of NASA/JPL/Malin Space Science Systems.

belief that Mars was warmer in the Noachian than it is today is also supported by the finding of evaporites at the Mars Exploration Rover landing site on Meridiani Planum and elsewhere, by evidence for fluctuation of the water table at Meridiani, by detection of clay minerals from orbit in Noachian terrains, by the presence of hydrothermally altered rocks in the Columbia Hills at the Mars Exploration Rover landing site in Gusev crater, and by surface erosion rates that were 4 to 5 orders of magnitude higher than they were subsequently.[23] These observations, in combination, suggest an Earth-like, active hydrological cycle with large lakes or oceans that acted as evaporative sources, sinks, and base levels for erosion. Given the likely large inventory of water at the surface, if Mars did have periods with an active hydrological cycle, oceans could have been present in lows such as Hellas and the northern plains (see Figure 7.1). However, although shorelines have been tentatively identified around both these lows, the observational evidence for the postulated oceans is weak.[24] In contrast, there is abundant evidence, such as deltas, of lakes in local lows within the uplands (Figure 2.4).

Although dissection of Noachian terrain is widespread, several morphological characteristics of the drainage basins suggest that, compared with those of Earth, the drainage system is immature.[25] The morphology of the Noachian terrains is dominated by primary terrain-building processes, such as impacts, volcanism, and deformation, rather than by fluvial processes. Even for the Noachian, for which researchers have the best evidence of abundant liquid water at the surface, the conditions necessary for fluvial erosion may have been achieved only episodically.

The Noachian was also characterized by high rates of volcanism and high rates of impact. The formation of large impact basins such as Hellas and Argyre would have had devastating effects on any emerging life.[26] Large fractions of any oceans present would have boiled away, and the planet would have been enveloped in hot-rock vapor that would have condensed and rained hot rock back onto the surface. Such global catastrophes would, however, have been separated by millions of years of relative quiet even in the era of heavy bombardment.

Although Mars appears to have had benign periods during the Noachian, when water flowed freely across the surface, the cause of the warmer conditions remains unknown. A thick CO_2-H_2O atmosphere may be incapable of warming the surface to above freezing without additional forms of heating such as infrared absorption by dust in the atmosphere.[27] Moreover, thick carbonate deposits that would contain CO_2 from a thick, early atmosphere have not been found despite intensive searches using orbital spectroscopy, although the CO_2 may have been lost to space instead. Another possibility is that large impacts or large volcanic eruptions episodically altered surface conditions temporarily,[28] thereby briefly stabilizing liquid water at the surface. At the end of the Noachian, the rate of formation of valley networks declined rapidly, although not to zero, erosion rates fell precipitously, and clay minerals appear to have stopped forming.[29] There can be little doubt that a major change in surface conditions occurred at the end of the Noachian.

Post-Noachian

The post-Noachian period, which encompasses roughly the last 3.8 billion years, is characterized by very low rates of weathering and erosion. The most characteristic fluvial feature of the post-Noachian era is the outflow channel, formed by large floods, rather than the valley networks that characterize the preceding era (Figure 2.5). Nevertheless, young valley networks are found in places, such as on young volcanoes, indicating that conditions necessary for slow erosion by running water were occasionally and locally met.

Large flood channels are readily recognizable by the scoured floors, streamlined walls, and tear-drop-shaped islands.[30] The largest are around the Chryse basin, into which several enormous channels converge. Peak discharges may have ranged as high as 10^8 m^3s^{-1}, as compared with 10^4 m^3s^{-1} for the Mississippi River. The Chryse channels emerge from local rubble-filled depressions, or from the Valles Marineris. Elsewhere channels may start at faults. The Chryse channels are mostly Hesperian in age (some 3.0 to 3.7 billion years ago), but crater dating of some channels elsewhere suggests that they can be as young as a few tens of millions of years.[31] If so, then floods could form today. The flood channels appear to have formed by eruptions of groundwater from below a thick cryosphere, or in the case of those adjacent to Valles Marineris, by the drainage of large lakes. Eruptions may have been triggered by a variety of causes such as large impacts, tectonic forces, or dike injection.

The best morphological evidence for volcano-ice interactions, and hence hydrothermal systems, is in the

BOX 2.1
Martian Geological Eras and the Age of Surface Features

The superposition of one surface feature (e.g., an impact crater) upon another (e.g., a lava flow) enables their relative ages to be determined. Thus, the impact crater is younger than the lava, which, in turn, is younger than the underlying surface of the planet. When such stratagraphic relationships are examined planet-wide, the history of Mars can be divided into three major geological eras, the Noachian, the Hesperian, and the Amazonian (Figure 2.1.1).[1]

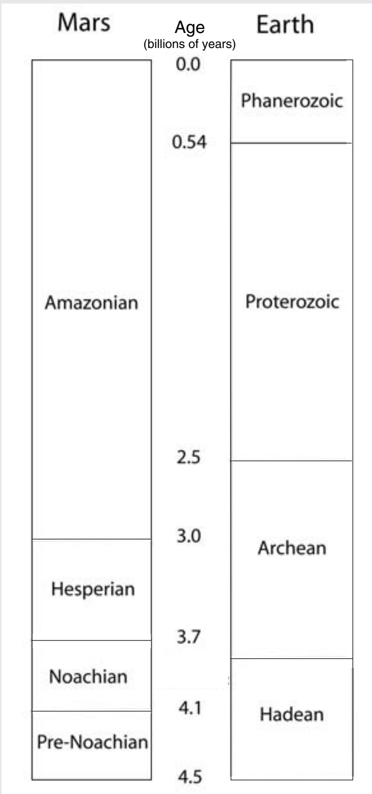


FIGURE 2.1.1 Major events in the geological histories of Earth and Mars over the last 4.5 billion years. The timing of the boundaries between Mars's three major named geological eras is highly uncertain because of the absence of an absolute calibration of the ages of martian surface features. Moreover, the geological record of the earliest events in martian history, those of the so-called pre-Noachian era, has been largely erased by subsequent events, including the heavy bombardment that took place during the Noachian era. Diagram courtesy of Michael H. Carr, U.S. Geological Survey.

Elysium region where several large fluvial channels emerge from graben radial to the volcanos there.[32] One possibility is that release of groundwater was caused by propagation of dikes radial to the volcanos through the local cryosphere and hydrosphere. Large bodies of water must have been left behind after the floods.[33] A thick cryosphere was probably present when the floods formed. Any terminal lakes or seas would thus have frozen, and ultimately the ice would have sublimated away or been buried. Observational evidence for any such oceans is sparse, although there is good evidence in the northern plains for burial of pre-flood craters and ridges by sediments,[34,35] and several features suggest the former presence of ice in the low areas at the ends of the channels (Figure 2.6).[36] It has been suggested that formation of a large flood would have temporarily changed global climates by injecting large amounts of H_2O and CO_2 into the atmosphere, but failure to detect carbonates is troubling. However, carbonate could be distributed uniformly throughout a crust, emplaced by circulation of water, and could hold a several-bar CO_2 atmosphere without being detectable spectroscopically. Also, thermal-emission spectrometer results have

The oldest geological features recognizable on Mars belong to the Noachian era, named after Noachis Terra in the southern highlands. In fact, most of Mars's rugged southern highlands are of Noachian age. This era was characterized by very high cratering rates and the formation of the major impact basins (e.g., Hellas and Argyre); major episodes of volcanic activity; and the formation of the oldest valley networks. Lying immediately atop Noachian geological units are features of the Hesperian era. Much of the northern lowlands and, in particular, the ridged plains are of Hesperian age. The youngest major surface features on Mars belong to the Amazonian era, so named because they are typified by the plains and volcanic materials of Amazonis Planitia. The surfaces of the prominent volcanos of Elysium and Tharsis Montes are of Amazonian age.

The absolute ages of martian features and thus the time history of the planet's evolution are currently uncertain. Converting the relative chronology implied by stratigraphy relationships requires that the absolute ages of key surface features be determined, and this will almost certainly require a sample-return mission. In the meantime, observations of the density of craters in a region can be used as a means of estimating that region's absolute age.[2] In other words, if a surface has a greater density of craters than an adjacent region and the rate at which impacts have occurred over time is known, then the ages of the surfaces can be estimated. Unfortunately, this technique is dependent on imperfect models of the cratering rate at Mars through time, which are, in turn, extrapolated from the known absolute chronology of the Moon.

Despite the very great uncertainties, particularly in the dating of the boundary between the Hesperian and the Amazonian, researchers estimate that the age limits of the major geological eras on Mars are as follows:

- Noachian era, ~4.1 billion to ~3.7 billion years ago;
- Hesperian era, ~3.7 billion to ~3 billion years ago; and
- Amazonian era, ~3 billion years ago to the present day.

Features older than the Noachian are usually referred to by the informal designation of pre-Noachian. Virtually nothing is known about this important period of martian history because the geological record of this time has been erased by later events. Unfortunately, this lost era includes the time in martian history when conditions might have most closely resembled those on Earth. By the end of the Noachian era, Mars was firmly established on a global evolutionary track that was significantly different from that followed by Earth over the subsequent 3.7 billion years.

[1]K.L. Tanaka, "The Stratigraphy of Mars," *Journal of Geological Research* 91:E139-E158, 1986.

[2]W.K. Hartmann and G. Neukum, "Cratering Chronology and the Evolution of Mars," pp. 165-194 in *Chronology and Evolution of Mars*, R. Kallenbach, J. Geiss, and W.K. Hartmann (eds.), Kluwer, Dordrecht, the Netherlands, 2001.

detected carbonates in the dust, and the martian meteorite ALH 84001 has several percent carbonates by weight, indicating that carbonates are present although the total quantity is unknown.

The martian canyons (e.g., Valles Marineris) are among the least understood features of the planet. Their relevance to liquid water and biology is that they may have once contained large lakes that ultimately drained catastrophically to the east to form outflow channels that connect to the canyons.[37] They also provide access via spectroscopy to the deep subsurface, where liquid water might have been present. Several large channels also start in box canyons to the north of the main canyons, indicating that liquid water was present locally at elevations well above the floor of the main canyons. The central and eastern sections of the canyons contain thick stacks of layered sediments, rich in sulfates, which could have been deposited subaqueously. However, even if the canyons did once contain lakes, as appears likely, the source of the sediments, their mode of deposition, and the lifetime of the lakes all remain undetermined.

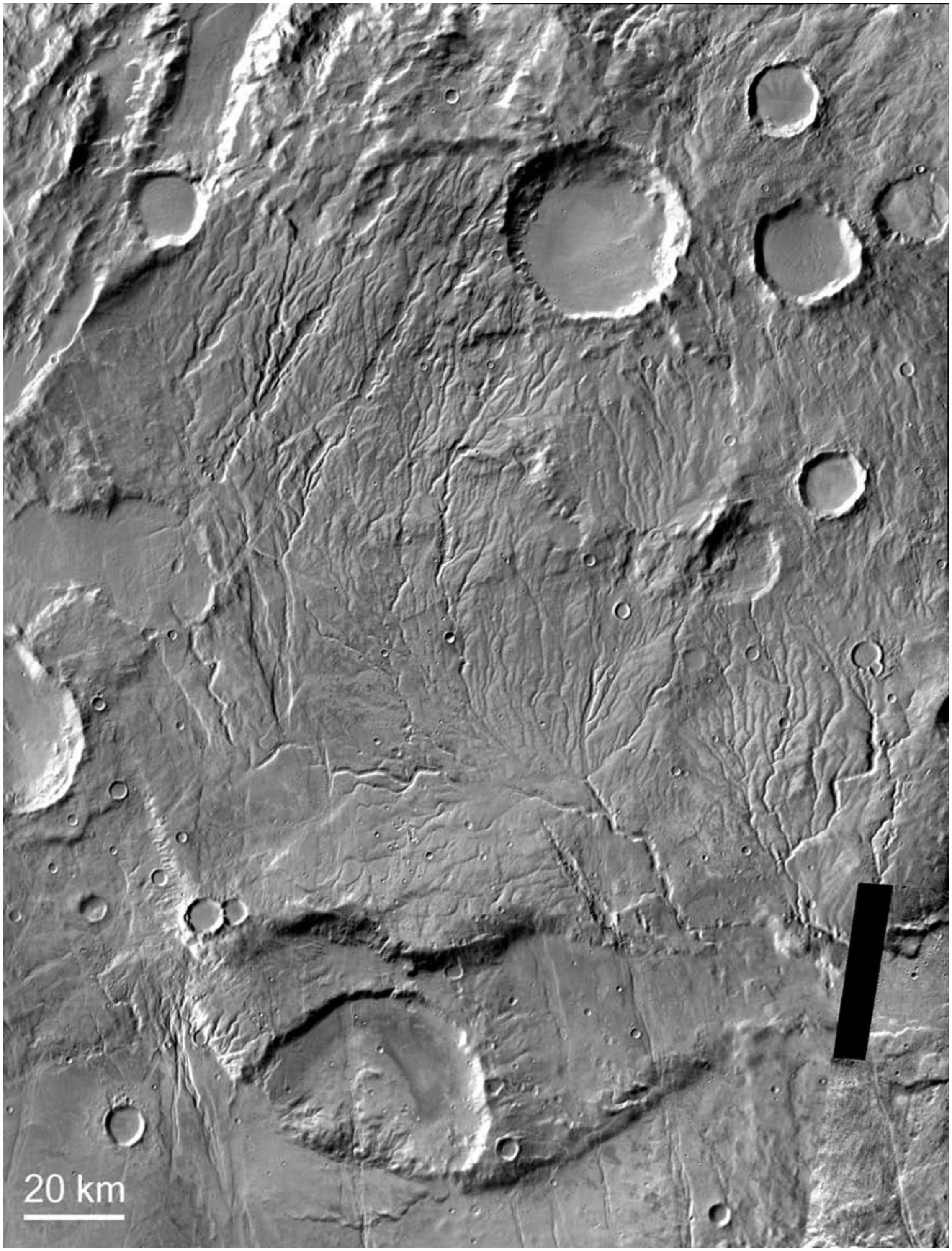


FIGURE 2.3 Warrego Vallis at 42°S, 267°E. The drainage density of this Noachian terrain is comparable to terrestrial values and implies precipitation and surface runoff. Image from the Thermal Emission Imaging System on the Mars Odyssey spacecraft courtesy of NASA/JPL/Arizona State University.

Although the rate of valley formation tailed off at the end of the Noachian, valleys continued to form at a low rate.[38] Some of the most prominent valleys such as Nirgal Vallis and Nanedi Vallis are Hesperian in age, but both these valleys have characteristics that suggest that they formed mainly by groundwater sapping rather than by surface runoff as is the case for most of the Noachian valleys (Figure 2.7).[39] Nevertheless, post-Noachian valley networks with runoff characteristics are found, as adjacent to Echus Chasma. In addition, several post-Noachian volcanos have surfaces that are highly dissected. In fact some of the most dissected surfaces anywhere are on volcanos. Several suggestions have been made to explain the young valleys on volcanos: that they formed by nuées ardentes or lava, that they formed during temporary warm periods caused by floods or large impacts, that they formed as a result of local conditions associated with volcanic eruptions, or that they resulted from the melting of ice deposited on the volcanos during periods of high obliquity, or after large floods. Whatever the cause, the presence of the valleys strongly supports the occasional temporary availability of liquid water on the volcano surfaces (Figure 2.8).

In summary, the present-day surface of Mars, with its cold temperatures, high ultraviolet flux, oxidizing conditions, and scarcity of liquid water and organics, is inhospitable to life as we know it. If life is present today, it likely is below the surface, protected from the harsh surface environment, or perhaps in exceedingly rare, localized environments driven by recent volcanic activity. The surface has experienced more benign conditions in the past, particularly the distant past. During the Noachian period, which ended around 3.7 billion years ago, liquid water was abundant at the surface, lakes were common, oceans may have been present, and the planet, like Earth, experienced high weathering rates with the production of clay minerals, and high rates of erosion and deposition, all consistent with warm, wet, habitable conditions.

At the end of the Noachian, conditions changed. Weathering and erosion rates declined rapidly to very low rates, which resulted in dominantly cold surface conditions and development of a thick cryosphere. Large floods episodically flowed across the surface leaving behind temporary lakes or seas, which could have proved temporary refuges. In addition, the planet intermittently experienced high obliquities that may have allowed accumulation of ice and snow at low latitudes, which on melting by sunlight or volcanic heat may have provided moist conditions in local areas. In all epochs, the combination of volcanism and water-rich conditions must have inevitably led to hydrothermal systems in which life could have thrived. Finally, accompanying these changes in physical processes were chemical changes.[40] Weathering in the Noachian (>3.7 billion years ago) produced clay minerals, which have not been detected in the younger (3.0 billion to 3.7 billion years old) Hesperian rocks. Instead, many Hesperian deposits are rich in sulfates, many of which may have formed in highly acidic waters. Alteration of the younger (<3.0 billion years ago) Amazonian rocks is mainly by oxidation.

LESSONS LEARNED FROM PRIOR INVESTIGATIONS ABOUT MARS AND POSSIBLE LIFE

There have been two prior detailed investigations into possible martian life. The lessons learned from these investigations have an important bearing on the search for life on another planet. In addition, recent measurements of possible methane in the martian atmosphere are important for the same reason—their potential relevance to searching for martian life.

The Viking Mission

Life detection was one of the major goals of the two Viking spacecraft that successfully landed on the martian surface in 1976. Each spacecraft carried three life-detection experiments designed to detect metabolism and, in addition, a gas chromatograph-mass spectrometer (GC-MS) to detect and identify organic compounds.[41] Overall, the results from the experiments were negative. The GC-MS detected no organic matter, and the results from the biology experiment all have plausible abiotic explanations.[42,43]

The GC-MS was, in principle, capable of detecting most organic compounds, except for highly polymerized, kerogen-like matter. Sensitivities were at the parts per billion level for compounds containing three or more carbon atoms and at the parts per million range for compounds containing one or two carbon atoms. Prior to the landings, it was thought that the soils would have detectable levels of organics from meteorite infall alone, and that photo-

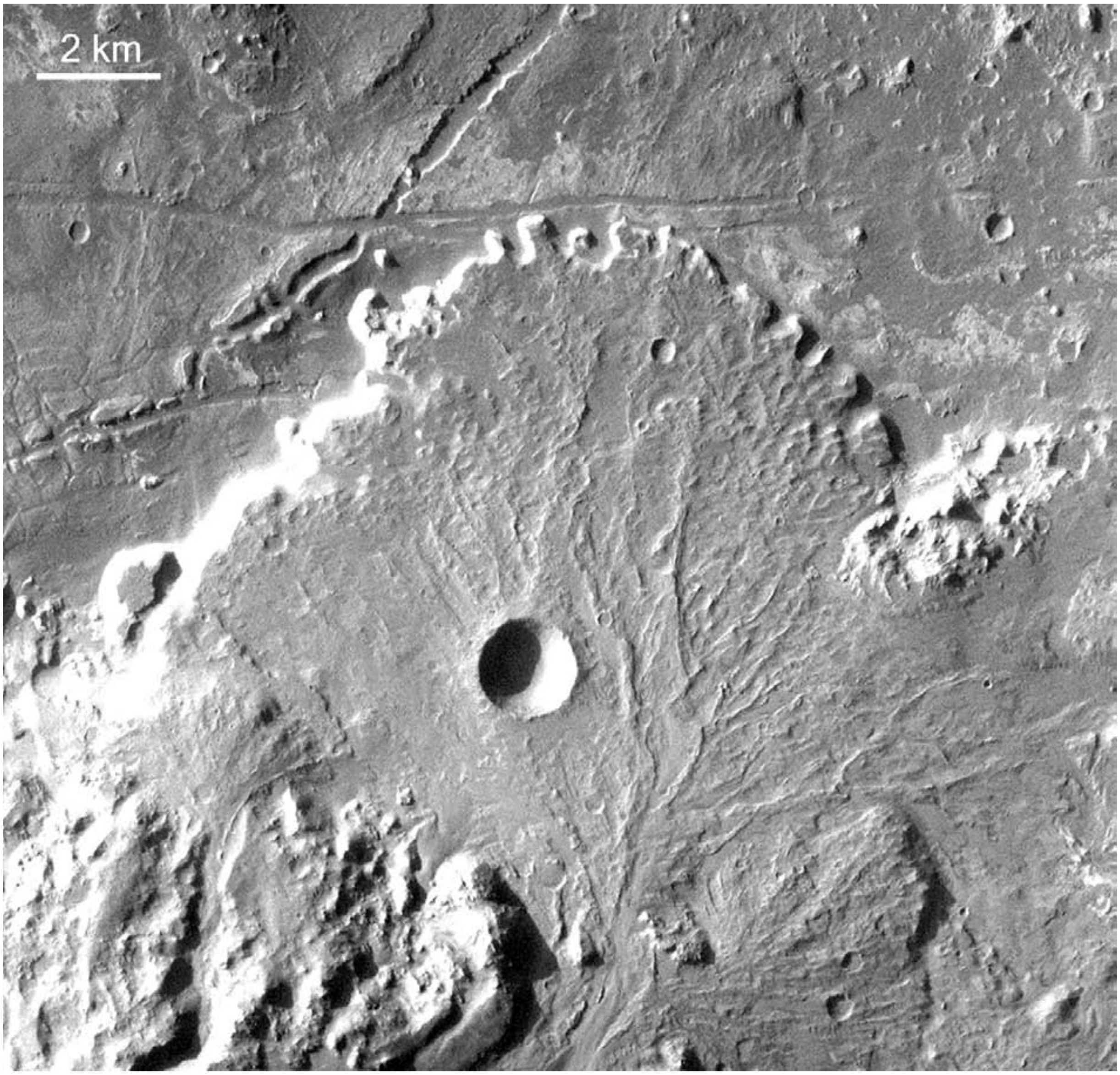


FIGURE 2.4 Delta in the Crater Holden at 27°S, 326°E. A stream has cut through the south rim of the crater, just visible at the bottom of the picture, and deposited its sediment load to form a fan within the crater. The branching ridges on the delta surface are former water courses left higher than their surroundings because of greater resistance to erosion. Image from the Thermal Emission Imaging System on the Mars Odyssey spacecraft courtesy of NASA/JPL/Arizona State University.

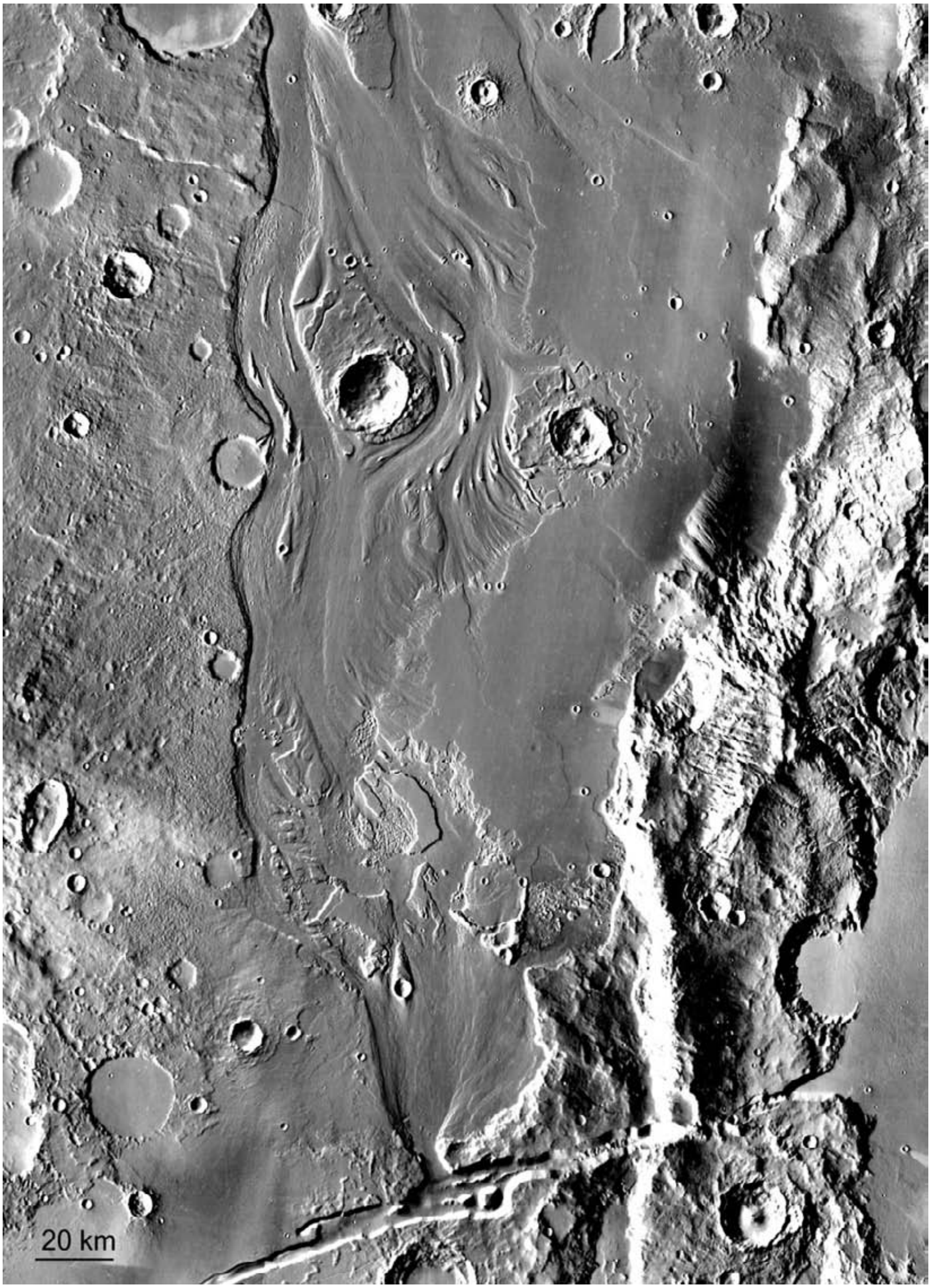


FIGURE 2.5 Mangala Vallis. The source of the outflow channel Mangala Vallis at 18°S, 210°E. The channel starts at a 7-km gap in a graben wall (bottom center) and then extends hundreds of kilometers northward. Faulting appears to have triggered massive release of groundwater. Image from the Thermal Emission Imaging System on the Mars Odyssey spacecraft courtesy of NASA/JPL/Arizona State University.

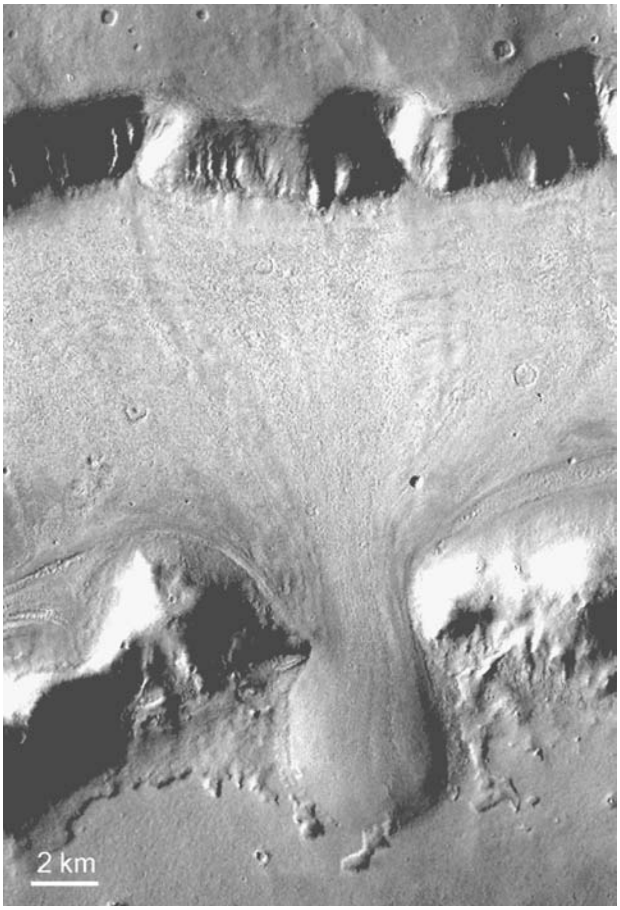


FIGURE 2.6 Ice-rich debris flows in the fretted terrain at 40°N, 25°E. At 30° to 50° latitudes in both hemispheres, material shed from slopes commonly shows indications of having flowed like glaciers. Here, what is probably an ice-rich debris flow has been deflected through a gap in an obstructing ridge. Image from the Thermal Emission Imaging System on the Mars Odyssey spacecraft courtesy of NASA/JPL/Arizona State University.

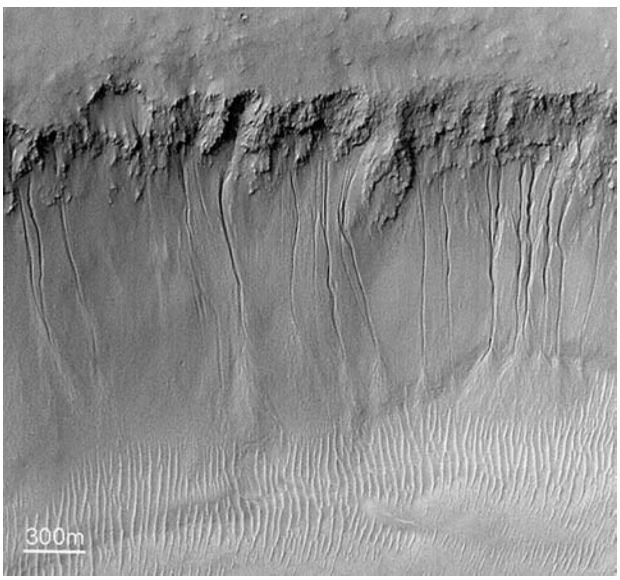


FIGURE 2.7 Gullies on the wall of Nirgal Vallis at 30°S, 321°E. Their origin is still being debated, but they formed recently and liquid water may have been involved in their formation. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems.

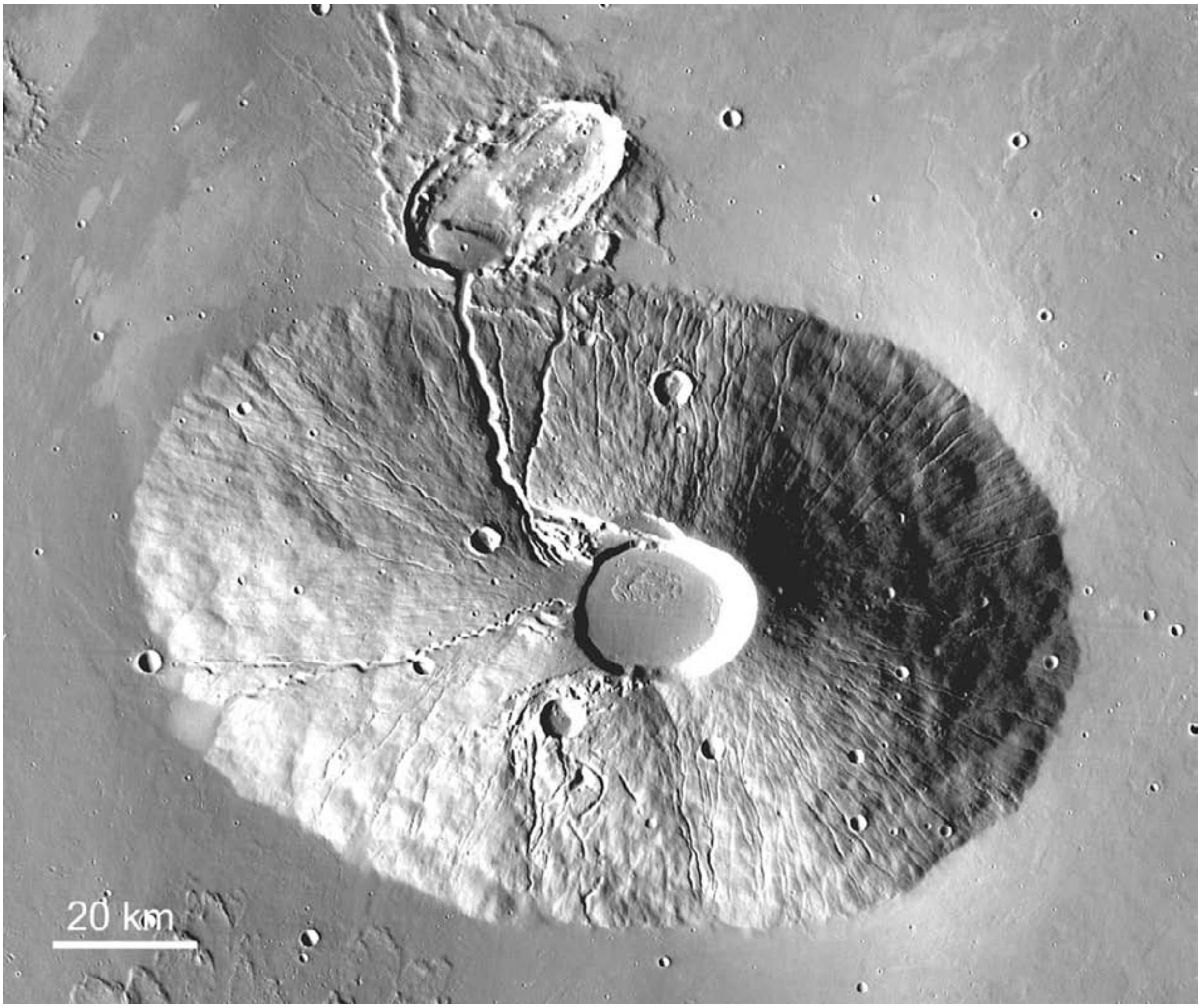


FIGURE 2.8 Ceraunius Tholus. Some volcanos, such as this, are densely dissected, possibly the result of melting of surface or subsurface ice by volcanic heat. Formation of the valleys may have been accompanied by hydrothermal activity. Image from the Thermal Emission Imaging System on the Mars Odyssey spacecraft courtesy of NASA/JPL/Arizona State University.

chemical fixation of CO into organics would be an additional contributor. Failure to detect organics implied that they are destroyed at the martian surface. One possible cause of the absence of organics is that they are destroyed by UV-stimulated reactions with metal oxides in the soils.[44] Another possibility is that they are destroyed by reactions with labile oxidants, since the biology experiments showed that in the presence of water, the soil releases tens to hundreds of nanomoles of O_2 per cubic centimeter.[45] The oxidants may be produced by photodissociation of water in the atmosphere. Another possibility is that organics were present but that oxidants in the soil destroyed them during sample processing by the GC-MS.[46]

In the pyrolytic-release experiment, isotopically labeled CO and CO_2 were added to the soil.[47] After a suitable incubation time, the gases were flushed out, and the soil was heated to see if any of the labeled carbon had been incorporated into less volatile species. Small amounts of carbon were fixed into organics, which the experimenters attributed to inorganic synthesis catalyzed by the martian soil. In a second gas-exchange experiment, the soil was humidified and nutrients added.[48] The resulting rapid release of oxygen was attributed to the presence of oxidants in the soil. In the third experiment, simple organic compounds labeled with radioactive tracers were added to the sample.[49] This resulted in rapid release of labeled gas followed by slow release. Subsequent experiments show that addition of the nutrients to soil containing Fe_2O_3 and H_2O_2 simulated the Viking results. The consensus is that all the results from the biology experiments have plausible inorganic explanations. A few researchers, however, maintain a contrary view.[50]

In retrospect, the Viking mission could be criticized as reaching too far too soon. In the late 1960s when the mission was conceived, knowledge of conditions on the martian surface was rudimentary. Speculations on the prospects for life were based largely on telescopic observations. Little information was available on the surface conditions and on where best to land in order to look for life. It could also be argued that the experiments were narrowly designed to detect a limited spectrum of terran life. Despite the negative results from the life-detection investigations, the Viking mission returned invaluable information for future biological experiments, such as data on the oxidizing nature of the surface and the possible scarcity of organics. In hindsight, the Viking missions constitute a compelling argument in favor of the kind of systematic approach advocated in this report and in NASA's 1995 report *An Exobiological Strategy for Mars Exploration*.[51]

The Search for Life on Early Earth and in the Martian Meteorite ALH 84001

The lack of a conclusive set of criteria for life detection and preservation has been illustrated recently by two debates: the search for the oldest evidence of life on Earth and the raging debate on the claims for life in ALH 84001. The scientific controversies over the former debate, that of the earliest evidence of life on Earth, have recently intensified but are still unresolved.[52–60] The common denominator in both of these debates is the underlying difficulty, or inability, to demonstrate conclusively the biological origin of the respective evidence.

The Earliest Life on Earth

Various claims and counterclaims have been published in the scientific literature in recent years concerning the earliest evidence for life on Earth.[61,62] The conflicting results of these studies illustrate the potential pitfalls in collecting and interpreting data from the ancient geological record.

Our planet's earliest known microfossils have been ascribed to 3.5-billion-year-old cyanobacteria identified by Schopf in samples of the Apex chert of Western Australia.[63] The morphological identification of these tiny dark clumps was always controversial, given that the range of bacterial morphologies at their simplest are ambiguous to interpret; bacteria have little morphology to begin with. Furthermore, the earliest evidence of biomarkers specific to cyanobacteria is 2.7 billion years ago, roughly consistent with molecular clock estimations of the emergence of cyanobacteria.[64] Such organisms would have produced photosynthetic oxygen, which does not appear as a significant atmospheric component until much later.[65,66]

The identification of these "microfossils" has been called into question by Brasier at al.,[67] based on reexamination of the chert sections of the original study. Many of the "microfossils"were observed to have branched morphologies inconsistent with filamentous bacteria. Schopf countered that the specimens are not branched, but folded by later deformations. In revisiting the collection site, Brasier et al. also determined that the Apex chert itself was not a sedimentary deposit, but instead was a vein formed by hydrothermal activity. Brasier et al. argued that the "microfossils" are merely bits of carbonaceous matter, unrelated to life, and squeezed out of forming quartz crystals and wrapped around them to resemble microfossils. To date no studies have satisfactorily determined the abiogenic or biogenic nature of the carbon forming the "pseudofossils."

To support his original claim, Schopf teamed with other scientists utilizing laser-Raman spectra to determine that carbon is present within the "microfossils."[68] However, other experts in this technique have criticized this work,[69] noting that there is nothing diagnostic in the spectra that indicates that the analyzed carbon-bearing clumps are the remains of organisms rather than abiotic organic matter.

The isotopic composition of carbon has been used as a biomarker, because photosynthetic organisms preferentially incorporate the lighter isotopes. Tiny bits of carbon (now graphite) in a 3.85-billion-year-old gneiss in Greenland have been determined to be depleted in ^{13}C.[70,71] The authors of this study suggested that the host rock was a sedimentary, banded iron formation. They hypothesized that biogenic matter collected at the bottom of the ocean and was incorporated into sediments; later metamorphism transformed the organic matter into graphite, but its carbon isotopic composition was preserved. They interpreted this finding as strong evidence for life, some 400 million years earlier than previously thought. In mapping the outcrop from which the samples were collected, other scientists have found that it is not a banded iron formation, but instead represents a volcanic rock into which metamorphic fluids were injected.[72] These fluids precipitated quartz to form the observed banding. This appears to be a highly unlikely site for the preservation of organisms. Moreover, it has now been shown that isotopically light hydrocarbons can be produced via several abiotic pathways.[73]

Although argument continues on both these controversies, most scientists appear to have sided with the skeptics. Several lessons can be drawn from these controversies about Earth's oldest life. Morphology alone is not a sufficient criterion for the identification of simple life forms. Understanding of the geological context of the sample is of prime importance, because it provides information on the environment in which the putative organism lived or was preserved. And, finally, the interpretation of geochemical analyses of extremely small samples is fraught with difficulty and sometimes ambiguity. In short, it is not enough to show that some chemical property is consistent with life, but it must also be inconsistent with abiotic formation.

ALH 84001

In August 1996, McKay et al. announced that they had found evidence for life in the martian meteorite ALH 84001,[74] a coarse-grained igneous rock (an orthopyroxenite) that crystallized 4.5 billion years ago. In support of their claim they listed the presence of the following:

- Objects shaped like bacteria in scanning electron microscope imagery,
- Polycyclic aromatic hydrocarbons (PAHs),
- Disequilibrium mineral assemblages, and
- Magnetic particles similar to magnetofossils produced by terran bacteria.

The claim of finding evidence for life in ALH 84001 is now viewed with skepticism.[75] The suggestion that some of the objects viewed in the meteorite at high resolution could be bacteria was immediately doubted because of the extremely small size of the objects. The bacteria-like forms are 100 nm long and as little as 20 to 30 nm wide, much smaller than the generally accepted size for the smallest bacteria. Although there are scattered reports in the biomedical literature of "organisms" of comparable size,[76] a panel convened by the National Research Council to assess how large an organism must be to enclose all the metabolic and genetic machinery that modern terran life requires concluded that independent free-living bacteria must be at least 200 to 300 nm in diameter.[77] Nevertheless, more recent results based on the use of genomic techniques have identified the so-called Archaeal Richmond Mine Acidophilic Nanoorganism, whose size is at or below the lower limit quoted in the NRC report.[78]

If the objects described by McKay et al. are organisms, they must have had a much simpler chemistry than even the simplest modern terran organism. Bradley et al.[79] alternatively suggested that the objects might be artifacts caused by the Au-Pd conductive coatings used by McKay et al. in the scanning electron microscope work. Similar objects have not been found when other coatings are used. There are reports of terran nanobacteria of comparable size to those in the martian meteorite,[80] but these claims are not widely accepted. Shortly after the publication by McKay et al., Anders pointed out that production of PAHs does not require biology.[81] Abiotic origins have been proposed for PAHs found in carbonaceous chondrites. Moreover, some phases (e.g., magnetite and clay minerals) associated with the carbonates in ALH 84001 are known to catalyze Fischer-Tropsch reactions, which convert simple carbon compounds such as CO into more complex ones, including PAHs. Anders also pointed out that the disequilibrium mineral assemblages described by McKay et al. could be produced abiotically. Finally, while the size, purity, morphology, and mineral structure of some of the magnetite grains in ALH 84001 do resemble those produced by terran magnetotactic bacteria, similar magnetites have been produced experimentally without the intervention of biology.[82] Indeed, some of the magnetites have growth textures suggesting that vapor condensation and shock vaporization of iron carbonate may account for these grains.

Lessons from Early Earth and ALH 84001

A review of the salient arguments for and against life both on early Earth and in martian meteorites reveals several positive points of note that must be addressed when looking for life on Mars:

- The demand for multiple lines of evidence, especially chemistry in addition to any morphological data. An integrated strategy relying on multiple instruments and measurements by independent investigators is necessary but not sufficient to build confidence in any positive claim for life detection.
- Both in situ and bulk inorganic and organic chemical analysis are needed to build up a fuller picture of the context of any interesting morphological features.
- The need to distinguish among disparate pools of carbon compounds, such as distinguishing compounds having an abiotic origin from those with a biotic or terrestrial contaminant origin. The potential pools of carbon contributing to the total organic carbon of a martian sample are shown in Table 2.1.
- The spatial and geological context and history from which the sample is taken are essential parameters in understanding the source of a potential biosignature.

The detailed mission objectives described by the Astrobiology Field Laboratory Science Steering Group provides one example of how these lessons have become an essential part of spacecraft mission planning.[83]

Methane

Mars has an atmosphere dominated by CO_2 with minor components of N_2, CO, O_2, H_2O, and Ar. Atmospheric investigations regarding the potential for life on Mars have focused on trace gases that could represent biomarkers. Examples include CH_4, H_2S, methyl mercaptans (CH_3SH), and N_2O. Recently three groups reported detection of methane with mixing ratios ranging up to 250 ppb,[84–86] with two of the reports, those of Formisano et al. and Mumma et al., suggesting spatial variations; however, these measurements are at the limit of detectability. If found to be correct, these observations would indicate that methane is being continuously released into the atmosphere since its calculated photochemical lifetime (<300 years) necessitates a continuing resupply. Verification of these findings awaits improvement in both precision and detection limits.

While initial excitement focused on the significance of methane as a potential biomarker, what is known about the planet is consistent with a variety of possible origins for methane.[87] Geological sources of methane include volcanic emissions and production of methane via low-temperature rock-water reactions as well as thermogenic gas from recycling of buried organic remnants from putative past life. The timing of methanogenesis is also complex, because spatial variation in methane in the atmosphere could result from ongoing methanogenesis as well as from intermittent release of gas stored over time in hydrates or subsurface fractures. Although an essential measurement, the isotopic composition of methane alone will not unambiguously distinguish between these biological and geological sources.[88] Resolution of the origin of methane requires integration of multiple lines of evidence that include the following:

- Verification of reported methane abundance in the atmosphere with higher sensitivity;
- Constraints on the spatial and temporal variations of methane abundances on the planet's surface; and
- Integration of chemical and isotopic analyses with data from a range of possible co-generated species to weigh the overall probability of origin.

A finding that might suggest methane production via ongoing or past biological processes would have obvious significance. Equally, indications of a geological origin for methane due to volcanic venting or significant water-rock alteration would significantly impact further investigation and exploration since such sites would have

TABLE 2.1 Possible Sources of Organic Carbon That Have to Be Distinguished in Martian Samples

Source of Carbon	Carbon Compounds, Examples, Comments
Abiotic molecules from meteoritic/ cometary influx	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, and sugars and sugar derivatives
Prebiotic/abiotic molecules from synthesis reaction process on Mars	Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, and sugars and sugar derivatives
Organic contamination from Earth	Condensation products derived from rocket exhaust, lubricants, plasticizers, atmospheric contaminants
Contaminating organisms from Earth	Whole cells, cell components (LPS, DNA, proteins, cytochromes).
Terran organisms, from Earth	Organisms not present on the craft measuring them, but previously transferred from Earth by either meteorite impact or contamination of previous spacecraft; target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be overexpressed or adapted in martian conditions
Terran organisms, evolved on Mars	Organisms that utilize terran biochemistries and have evolved on Mars; target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be overexpressed or adapted in martian conditions or organisms using metabolisms that would not be present on a spacecraft contaminant such as methanogens, or psychrophiles with endolithic survival mechanisms
Non-terran organisms	Organisms that utilize an array of molecules for information storage, information transfer, compartmentalization, and enzymatic activity that differ from those used by extant terran life; examples include the use of novel amino acids and nucleotides or the use of novel nitrogen utilization strategies
Fossil biomarkers	Established terrestrial fossil biomarkers such as hopanes, archaeal lipids, and steranes for detection of the diagenetic remains of terran life; characterization of potential breakdown products that can be reasonably extrapolated from the detection of molecules constituting an extant martian life form; detection of the diagenesis products of fossil martian organisms based on carbon compositions consistent with biological fractionation of a narrow range of abiotic precursors

many of the characteristics potentially conducive for life. Either way, a confirmation of the mechanism for origin of methane in the Mars atmosphere would have important implications for astrobiology.

REFERENCES

1. P.B. Price and T. Sowers, "Temperature Dependence of Metabolic Rates for Microbial Growth, Maintenance, and Survival," *Proceedings of the National Academy of Sciences* 101(13):4631-4636, doi:10.1073/pnas.0400522101, 2004.

2. R.Y. Morita, *Bacteria in Oligotrophic Environments*, Chapman and Hall, New York, 1997.

3. D.G. Capone, R. Popa, B. Flood, and K.H. Nealson, "Follow the Nitrogen," *Science* 312:708-709, 2006.

4. See, for example, Table 5.1 in National Research Council, *Preventing the Forward Contamination of Mars*, National Academies Press, Washington, D.C., 2006, p. 71.

5. D. Beaty, K. Buxbaum, M. Meyer, N. Barlow, W. Boynton, B. Clark, J. Deming, P.T. Doran, K. Edgett, S. Hancock, J. Head, M. Hecht, V. Hipkin, T. Kieft, R. Mancinelli, E. McDonald, C. McKay, M. Mellon, H. Newsom, G. Ori, D. Paige, A.C. Schuerger, M. Sogin, J.A. Spry, A. Steele, K. Tanaka, and M. Voytek, "Findings of the Mars Special Region Science Analysis Group," *Astrobiology* 6(5):677-732, 2006.

6. P.B. Price and T. Sowers, “Temperature Dependence of Metabolic Rates for Microbial Growth, Maintenance, and Survival,” *Proceedings of the National Academy of Sciences* 101(13):4631-4636, doi:10.1073/pnas.0400522101, 2004.

7. K. Kashefi and D.R. Lovley, “Extending the Upper Limits of Life,” *Science* 301:93, 2003.

8. M.O. Schrenk, D.S. Kelley, J.R. Delaney, and J.A. Baross, “Incidence and Diversity of Microorganisms Within the Walls of an Active Deep-Sea Sulfide Chimney,” *Applied and Environmental Microbiology* 69(6):3580-3592, 2003.

9. W.D. Grant, “Life at Low Water Activity,” *Phil. Trans. R. Soc. Lond. B* 359:1249-1267, doi:10.1098/rstb.2004.1502, 2004.

10. D. Beaty, K. Buxbaum, M. Meyer, N. Barlow, W. Boynton, B. Clark, J. Deming, P.T. Doran, K. Edgett, S. Hancock, J. Head, M. Hecht, V. Hipkin, T. Kieft, R. Mancinelli, E. McDonald, C. McKay, M. Mellon, H. Newsom, G. Ori, D. Paige, A.C. Schuerger, M. Sogin, J.A. Spry, A. Steele, K. Tanaka, and M. Voytek, “Findings of the Mars Special Region Science Analysis Group,” *Astrobiology* 6(5):677-732, 2006.

11. D.G. Capone, R. Popa, B. Flood, and K.H. Nealson, “Follow the Nitrogen,” *Science* 312:708-709, 2006.

12. L.A. Haskins, A. Wang, H.Y. McSween, B.C. Clark, D.J. Des Marais, S.M. McLennan, N.J. Tosca, J.A. Hurowitz, J.D. Farmer, A. Yen, S.W. Squyres, R.E. Arvidson, G. Klingelhöfer, C. Schröder, P.A. de Souza, Jr., D.W. Ming, R. Gellert, J. Zipfel, J. Brückner, J.F. Bell, III, K. Herkenhoff, P.R. Christensen, S. Ruff, D. Blaney, S. Gorevan, N.A. Cabrol, L. Crumpler, J. Grant, and L. Soderblom, “Water Alteration of Rocks and Soils on Mars and the Spirit Rover Site in Gusev Crater,” *Nature* 436:66-69, 2005.

13. H.P. Klein, “The Viking Mission and the Search for Life on Mars,” *Reviews of Geophysics* 17:1655-1662, 1979.

14. See, for example, P.B. James, H.H. Kieffer, and D.A. Paige, “The Seasonal Cycle of Carbon Dioxide on Mars,” pp. 934-968 in H.H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews (eds.), *Mars*, University of Arizona Press, Tucson, Arizona, 1992.

15. See, for example, B.M. Jakosky and M.T. Mellon, “Water on Mars,” *Physics Today* 57(4):71-76, 2004.

16. See, for example, H.H. Kieffer and A.P. Zent, “Quasi-periodic Climate Change on Mars,” pp. 1180-1218 in H.H. Kieffer, B.M. Jakosky, C.W. Snyder, and M.S. Matthews (eds.), *Mars*, University of Arizona Press, Tucson, Arizona, 1992.

17. W.C. Feldman, T.H. Prettyman, S. Maurice, J.L. Plaut, D.L. Bish, D.T. Vaniman, M.T. Mellon, A.E. Metzger, S.W. Squyres, S. Karunatillake, W.V. Boynton, R.C. Elphic, H.O. Funsten, D.J. Lawrence, and R.L. Tokar, “The Global Distribution of Near Surface Hydrogen on Mars,” *Journal of Geophysical Research* 109(E9):E09006, doi:10.1029/2003JE02160, 2004.

18. M.C. Malin, K.S. Edgett, L.V. Posiolova, S.M. McColley, and E.Z. Noe Dobrea, “Present-Day Impact Cratering Rate and Contemporary Gully Activity on Mars,” *Science* 314:1573-1577, 2006.

19. P.R. Christensen, “Formation of Recent Martian Gullies Through Melting of Extensive Water-rich Snow Deposits,” *Nature* 422:45-48, 2003.

20. J. Laskar, A.C.M Correia, M. Gastineau, F. Joutel, B. Levrard, and P. Robutel, “Long Term Evolution and Chaotic Diffusion of the Insolation Quantities of Mars,” *Icarus* 170:343-364, 2004.

21. F. Costard, F. Forget, N. Mangold, and J.P. Peulvast, “Formation of Recent Martian Debris Flows by Melting of Near-surface Ground Ice at High Obliquity,” *Science* 295:110-113, 2002.

22. See, for example, L. Borg and M.J. Drake, “A Review of Meteorite Evidence for the Timing of Magmatism and of Surface or Near-surface Liquid Water on Mars,” *Journal of Geophysical Research* 110:E12S03, doi:1029/2005JE002402, 2005.

23. M.H. Carr, *The Surface of Mars*, Cambridge University Press, Cambridge, 2006.

24. M.H. Carr and J.E. Head, “Oceans on Mars: An Assessment of Observational Evidence and Possible Fate,” *Journal of Geophysical Research* 108(E5):5042-5070, 2003.

25. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

26. N.H. Sleep and K. Zahnle, “Refugia from Asteroid Impact on Early Mars and the Early Earth,” *Journal of Geophysical Research* 103(E12):28529-28544, 1998.

27. R.M. Haberle, “Early Climate Models,” *Journal of Geophysical Research* 103(E12):28467-28479, 1998.

28. T.L. Segura, O.B. Toon, A. Colaprete, and K. Zahnle, “Environmental Effects of Large Impacts,” *Science* 298:1977-1980, 2002.

29. J. Bibring, Y. Langevin, J.F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold, P. Pinet, F. Forget, and the OMEGA team M. Berthé, J. Bibring, A. Gendrin, C. Gomez, B. Gondet, D. Jouglet, F. Poulet, A. Soufflot, M. Vincendon, M. Combes, P. Drossart, T. Encrenaz, T. Fouchet, R. Merchiorri, G. Belluci, F. Altieri, V. Formisano, F. Capaccioni, P. Cerroni, A. Coradini, S. Fonti, O. Korablev, V. Kottsov, N. Ignatiev, V. Moroz, D. Titov, L. Zasova, D. Loiseau, N. Mangold, P. Pinet, S. Douté, B. Schmitt, C. Sotin, E. Hauber, H. Hoffmann, R. Jaumann, U. Keller, R. Arvidson, J.F. Mustard, T. Duxbury, F. Forget, and G. Neukum, “Global Mineralogical and Aqueous Mars History Derived from OMEGA/Mars Express Data,” *Science* 312:400-404, 2006.

30. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

31. D.M. Burr, A.S. McEwen, and S.E. Sakimoto, "Recent Aqueous Floods from the Cerberus Fossae, Mars," *Geophysical Research Letters* 29:1, 2002. doi:10.1029/2001Gl013345.

32. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

33. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

34. M.A. Kreslavsky, and J.W. Head, "Fate of Outflow Channel Effluents in the Northern Lowlands of Mars: The Vastitas Borealis Formation as a Sublimation Residue from Frozen, Ponded Bodies of Water," *Journal of Geophysical Research* 107(E12):5121, doi:10.1029/2001JE001831, 2002.

35. J. Laskar, A.C.M Correia, M. Gastineau, F. Joutel, B. Levrard, and P. Robutel, "Long Term Evolution and Chaotic Diffusion of the Insolation Quantities of Mars," *Icarus* 170:343-364, 2004.

36. J.S. Kargel, V.R. Baker, J.E. Beget, J.E. Lockwood, T.L. Péwé, J.S. Shaw, and R.G. Strom, "Evidence for Ancient Continental Glaciation in the Martian Northern Plains," *Journal of Geophysical Research* 100:5351-5368, 1995.

37. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

38. M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y., 2006.

39. See, for example, M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y. 2006; and references therein.

40. J. Bibring, Y. Langevin, J.F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold, P. Pinet, F. Forget, and the OMEGA team M. Berthé, J. Bibring, A. Gendrin, C. Gomez, B. Gondet, D. Jouglet, F. Poulet, A. Soufflot, M. Vincendon, M. Combes, P. Drossart, T. Encrenaz, T. Fouchet, R. Merchiorri, G. Belluci, F. Altieri, V. Formisano, F. Capaccioni, P. Cerroni, A. Coradini, S. Fonti, O. Korablev, V. Kottsov, N. Ignatiev, V. Moroz, D. Titov, L. Zasova, D. Loiseau, N. Mangold, P. Pinet, S. Douté, B. Schmitt, C. Sotin, E. Hauber, H. Hoffmann, R. Jaumann, U. Keller, R. Arvidson, J.F. Mustard, T. Duxbury, F. Forget, and G. Neukum, "Global Mineralogical and Aqueous Mars History Derived from OMEGA/Mars Express Data," *Science* 312:400-404, 2006.

41. See, for example, H.P. Klein, "The Viking Biological Investigations: General Aspects," *Journal of Geophysical Research* 82:4677-4680, 1977.

42. K. Biemann, J. Oro, P. Toulmin III, L.E. Orgel, A.O. Nier, D.M. Anderson, D. Flory, A.V. Diaz, D.R. Rushneck, and P.G. Simmonds, "The Search for Organic Substances and Inorganic Volatile Compounds in the Surface of Mars," *Journal of Geophysical Research* 82:4641-4662, 1977.

43. H.P. Klein, "The Search for Life on Mars," *Review Geophysics and Space Physics* 17:1655-1662, 1979.

44. D.Y. Sumner, "Poor Preservation Potential of Organics in Meridiani Planum Hematite-bearing Sedimentary Rocks," *Journal of Geophysical Research* 109:E12007, doi:10.1029/2004JE002321, 2004.

45. K. Biemann, J. Oro, P. Toulmin III, L.E. Orgel, A.O. Nier, D.M. Anderson, D. Flory, A.V. Diaz, D.R. Rushneck, and P.G. Simmonds, "The Search for Organic Substances and Inorganic Compounds in the Surface of Mars," *Journal of Geophysical Research* 82:4641-4658, 1977.

46. R. Navarro-Gonzalez, K.F. Navarro, J. de la Rosa, E. Iñiguez, P. Molina, L.D. Miranda, P. Morales, E. Cienfuegos, P. Coll, F. Raulin, R. Amils, and C.P. McKay, "The Limitations on Organic Detection in Mars-like Soils by Thermal Volatilization–Gas Chromatography–MS and their Implications for the Viking Results," *Proceedings of the National Academy of Sciences* 103:16089-16094, 2006.

47. N.H. Horowitz, G.L. Hobby, and J.S. Hubbard, "Viking on Mars: The Carbon Assimilation Experiments," *Journal of Geophysical Research* 82:4659-4662, 1977.

48. V.I. Oyama and B.J. Berdahl, "The Viking Gas Exchange Experiment Results from Chryse and Utopia Surface Samples," *Journal of Geophysical Research* 82:4669-4676, 1977.

49. V.V. Levin and P.A. Straat, "Recent Results from the Viking Labeled Release Experiment on Mars," *Journal of Geophysical Research* 82:4663-4667, 1977.

50. See, for example, G.V. Levin, "The Viking Labeled Release Experiment and Life on Mars," *SPIE Proceedings* 3111:146-161, 1997.

51. National Aeronautics and Space Administration, *An Exobiology Strategy for Mars Exploration*, National Aeronautics and Space Administration, Washington, D.C., 1995.

52. M. Schidlowski, "A 3,800 Million Year Isotopic Record of Life from Carbon in Sedimentary Rocks," *Nature* 333:313-318, 1988.

53. J.W. Schopf "Microfossils of the Early Archaean Apex Chert: New Evidence of the Antiquity of Life," *Science* 260:640-646, 1993.

54. S.J. Mojzsis, G. Arrhenius, K.D. McKeegan, T.M. Harrison, A.P. Nutman, and C.R. Friend, "Evidence for Life on Earth Before 3,800 Million Years Ago," *Nature* 384:55-59, 1996.

55. M.T. Rosing, "^{13}C-depleted Carbon Microparticles in >3700 Ma Sea-floor Sedimentary Rocks from West Greenland," *Science* 283:674-676, 1999.

56. S.J. Mojzsis and T.M. Harrison, "Vestiges of a Beginning: Clues to the Emergent Biosphere Recorded in the Oldest Known Sedimentary Rocks," *Geological Society of America Today* 10:1-7, 2000.

57. M.D. Brasier, O.R. Green, A.P. Jephcoat, A.K. Kleppe, M.J. Van Kranendonk, J.F. Lindsay, A. Steele, and N.V. Grassineau, "Questioning the Evidence for Earth's Oldest Fossils," *Nature* 416:76-81, 2002.

58. C.M. Fedo and M.J. Whitehouse, "Metasomatic Origin of Quartz-Pyroxene Rock, Akilia, Greenland, and Implications for Earth's Earliest Life," *Science* 296:1448-1452, 2002.

59. J.D. Pasteris and B. Wopenka, "Laser Raman Spectroscopy: Images of the Earth's Earliest Fossils?," *Nature* 420:476-477, 2002.

60. H. Furnes, N.R. Banerjee, K. Muehlenbachs, H. Staudigel, and M. de Wit, "Life Recorded in Archean Pillow Lavas," *Science* 304:578, 2004.

61. See, for example, R.A. Kerr, "Reversals Reveal Pitfalls in Spotting Ancient and E.T. Life," *Science* 296:1384-1385, 2002.

62. See, for example, R. Dalton, "Microfossils: Squaring Up Over Ancient Life," *Nature* 417:782-784, 2002.

63. J.W. Schopf "Microfossils of the Early Archaean Apex Chert: New Evidence of the Antiquity of Life," *Science* 260:640-646, 1993.

64. J.J. Brocks, G.A. Logan, R. Buick, and R.E. Summons, "Archean Molecular Fossils and the Early Rise of Eukaryotes," *Science* 285:1033-1036, 1999.

65. J.J. Brocks, G.A. Logan, R. Buick, and R.E. Summons, "Archean Molecular Fossils and the Early Rise of Eukaryotes," *Science* 285:1033-1036, 1999.

66. S.B. Hedges, J.E. Blair, M.L. Venturi, and J.L. Shoe, "A Genomic Timescale for the Origin of Eukaryotes and the Rise of Complex Multicellular Life," *BMC Evolutionary Biology* 1:4, 2001.

67. M.D. Brasier, O.R. Green, A.P. Jephcoat, A.K. Kleppe, M.J. Van Kranendonk, J.F. Lindsay, A. Steele, and N.V. Grassineau, "Questioning the Evidence for Earth's Oldest Fossils," *Nature* 416:76-81, 2002.

68. J.W. Schopf, A.B. Kudryavtsev, D.G. Agresti, T.J. Wdowiak, and A.D. Czaja, "Laser-Raman Imagery of Earth's Oldest Fossils," *Nature* 416:73-76, 2002.

69. See, for example, J.D. Pasteris and B. Wopenka, "Laser Raman Spectroscopy: Images of the Earth's Earliest Fossils?" *Nature* 420:476-477, 2002.

70. S.J. Mojzsis, G. Arrhenius, K.D. McKeegan, T.M. Harrison, A.P. Nutman, and C.R. Friend, "Evidence for Life on Earth Before 3,800 Million Years Ago," *Nature* 384:55-59, 1996.

71. S.J. Mojzsis and T.M. Harrison, "Vestiges of a Beginning: Clues to the Emergent Biosphere Recorded in the Oldest Known Sedimentary Rocks," *Geological Society of America Today* 10:1-7, 2000.

72. C.M. Fedo and M.J. Whitehouse, "Metasomatic Origin of Quartz-Pyroxene Rock, Akilia, Greenland, and Implications for Earth's Earliest Life," *Science* 296:1448-1452, 2002.

73. For a summary, see, for example, C.M. Fedo, M.J. Whitehouse, and B.S. Kamber, "Geological Constraints on Detecting the Earliest Life on Earth: A perspective from the Early Archaean (older than 3.7 Gyr) of Southwest Greenland," *Philosophical Transactions of the Royal Society B* 361:851-867, 2006.

74. D.S. McKay, E.K. Gibson, Jr., K.L. Thomas-Keprt, H. Vali, C.S. Romanek, S.J. Clemett, X.D.F. Chillier, C.R. Maechling, and R.N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH 84001," *Science* 273:924-930, 1996.

75. See, for example, D.J. DesMarais, B.M. Jakosky, and B.M. Hynek, "Astrobiological Implications of Mars Surface Composition and Properties," in *The Martian Surface: Composition, Mineralogy, and Physical Properties*, J.F. Bell III, ed., Cambridge University Press, Cambridge, U.K., in press.

76. See, for example, E.O. Kajander, M. Bjorklund, and N. Ciftcioglu, "Suggestions from Observations on Nanobacteria Isolated from Blood," pp. 50-55, and references therein, in National Research Council, *Size Limits of Very Small Microorganisms: Proceedings of a Workshop*, National Academy Press, Washington, D.C., 1999.

77. National Research Council, *Size Limits of Very Small Microorganisms: Proceedings of a Workshop*, National Academies Press, Washington D.C., 1999.

78. B.J. Baker, G.W. Tyson, R.I. Webb, J. Flanagan, P. Hugenholtz, E.E. Allen, and J.F. Banfield, "Lineages of Acidophilic Archaea Revealed by Community Genomic Analysis," *Science* 314:1933-1935, 2006.

79. J.P. Bradley, R.P. Harvey, and H.Y. McSween, "No 'Nanofossils' in Martian Meteorite," *Nature* 390:454, 1997.

80. See for example R.L. Folk, "SEM Imaging of Bacteria and Nanobacterial in Carbonate Sediments and Rocks," *Journal of Sedimentary Petrology* 63:990-999, 1993.

81. E. Anders, "Evaluating the Evidence for Past Life on Mars," *Science* 274:2119-2120, 1996.

82. D.C. Golden, D.W. Ming, R.V. Morris, A. Brearley, H.V. Lauer, A.H. Treiman, M.E. Zolensky, C.S. Schwandt, G.E. Lofgren, and G.A. McKay, "Evidence for Exclusively Inorganic Formation of Magnetite in Martian Meteorite ALH 84001," *American Mineralogist* 89:681-695, 2004.

83. A. Steele, D.W. Beaty, J. Amend, R. Anderson, L. Beegle, L. Benning, J. Bhattacharya, D. Blake, W. Brinckerhoff, J. Biddle, S. Cady, P. Conrad, J. Lindsay, R. Mancinelli, G. Mungas, J. Mustard, K. Oxnevad, J. Toporski, and H. Waite, "The Astrobiology Field Laboratory," Unpublished white paper, 72 p, posted Dec., 2005 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

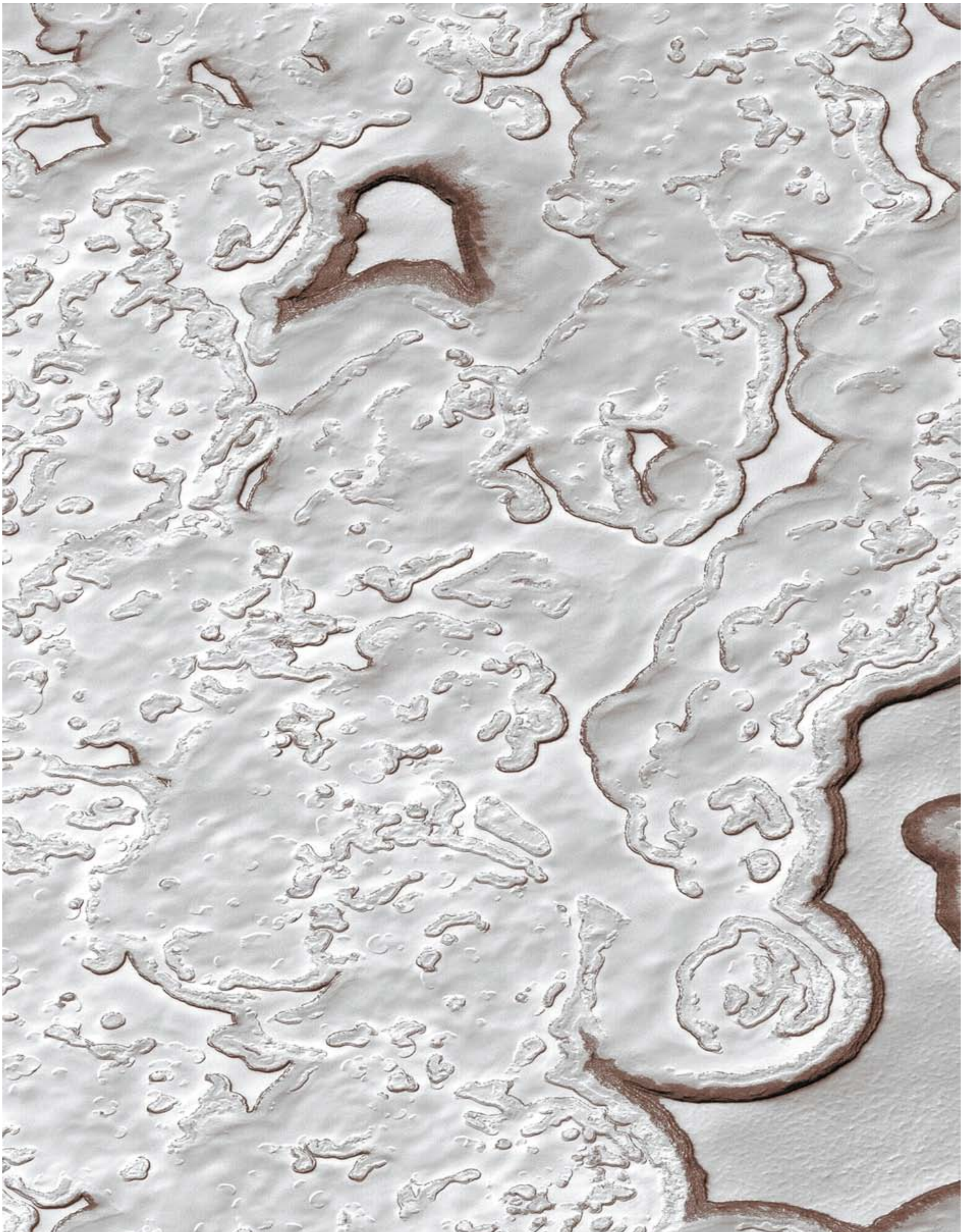
84. V. Formisano, S. Atreva, T. Encrenaz, N. Ignatiev, and M. Giuranna, "Detection of Methane in the Atmosphere of Mars," *Science* 306:1758-1761, 2004.

85. V.A. Krasnopolsky, J.P. Maillard, and T.C. Owen, "Detection of Methane in the Martian Atmosphere: Evidence for life?" *Icarus* 172:537-547, 2004.

86. M.J. Mumma, R.E. Novak, M.A. DiSanti, B.P. Bonev, and N. Dello Russo, "Detection and Mapping of Methane and Water on Mars," *Bulletin of the American Astronomical Society* 36:1127, 2004.

87. M. Allen, B. Sherwood Lollar, B. Runnegar, D.Z. Oehler, J.R. Lyons, C.E. Manning, and M.E. Summers, "Is Mars Alive?," *Eos* 87(41):433-448, 2006.

88. M. Allen, B. Sherwood Lollar, B. Runnegar, D.Z. Oehler, J.R. Lyons, C.E. Manning, and M.E. Summers, "Is Mars Alive?," *Eos* 87(41):433-448, 2006.



3

Biosignatures and Abiotic Chemistry

Life as we know it (i.e., terran life, as discussed in Chapter 1) is based on organic chemistry and is constructed of carbonaceous compounds. These organic materials are pervasive in Earth's crust and constitute an extensive chemical and isotopic record of past life that far exceeds what is recorded by visible fossils.[1] The ubiquity of coal, organic-rich black shales, and petroleum hydrocarbons, for example, is one manifestation of life's activities that extends deep into the geological record and can be used to observe past biological activity and events.[2] In fact, biogenic organic matter is so ubiquitous and overwhelming in its abundance that it is exceedingly difficult to identify organic compounds and organic matter of unambiguously nonbiological origin. The notable exceptions are organic compounds in meteorites and synthetics.[3]

Experience with studies of terrestrial materials suggests that of all the various life-detection techniques available, analysis of carbon chemistry is the first among equals. Imaging and other life-detection techniques are important and will always be part and parcel of planetary exploration, but few would assert that any single methodology provides a more robust way to find extraterrestrial life than organic analysis. Accordingly, the prime emphasis here is on chemical methods for life detection. However, organic analysis alone is insufficient to detect life. The results from an ensemble of all of the relevant methodologies, combined with considerations of geological and environmental plausibility, will likely provide the best evidence for the presence or absence of life in a sample.

Although all of the assumed characteristics of hypothetical martian life forms discussed in Chapter 1 can inform and guide the overall search for biosignatures, the assumption concerning the key role likely to be played by organic chemistry will prove to be particularly important. This assumption implies that martian organisms would produce and use a wide range of small molecules and organic polymers that could serve as chemical biosignatures in their intact or fragmentary states. But to apply this knowledge for remote sensing experiments on Mars or other planetary bodies, astrobologists need to distinguish reliably between biological molecules and those that are non-biological in origin. The following discussion identifies specific features that distinguish abiotic compounds from compounds or patterns produced by present-day life on Earth. To address the past geocentric focus, the discussion

FIGURE 3.1 This image shows a portion of the residual southern polar cap. The carbon dioxide has sublimated to expose underlying water ice. Changes from year to year suggest that in the present epoch the amount of carbon dioxide in the residual cap is decreasing. This image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft is courtesy of NASA/JPL/Malin Space Science Systems. The image covers an area of 2.9 by 4.8 km.

considers some generic features that could not be generated abiologically and that would be the foundation of a sound approach to the recognition of nonterran life.

ABIOTIC CHEMISTRY

Abiotic chemistry, both organic and inorganic, provides important information about the pathways that might have led toward an origin of life. Unfortunately, there is in origin-of-life scenarios no consensus about the synthesis of organics on early Earth or elsewhere, and so astrobiologists cannot search for a specific chemistry. Among the models suggested as possibly relevant for the origin of life are atmospheric electric discharges, as proposed by Miller and Urey,[4] which have been shown to synthesize a range of organic compounds, including amino acids, from mixtures of methane, ammonia, and water. Discharge experiments yield few organic compounds when carried out in the kinds of oxidized gas mixtures of carbon dioxide thought to have predominated on early Mars. Additional processes that might have contributed to the inventory of organic compounds on early Mars include those associated with the transient effects of bolide impacts[5] and, more importantly, a variety of mineral-catalyzed chemical reactions including water-rock reactions (e.g., serpentinization) and Strecker, Fischer-Tropsch, and FeS-driven organic synthesis.[6] Water-rock reactions produce copious amounts of hydrogen that could lead to the subsurface formation of hydrocarbons from carbon dioxide and have also been shown to reduce nitrogen to ammonia,[7] both of which could make their way to planetary surfaces. Strecker synthesis is the reaction of ammonia, hydrogen cyanide, and aldehydes to give amino acids and related products. Fischer-Tropsch chemistry is the mineral-catalyzed high-temperature reaction of carbon monoxide and hydrogen to give hydrocarbons. FeS-driven organic synthesis, first proposed by Wächtershäuser,[8,9] has been experimentally demonstrated for only a relatively limited set of syntheses.

It is safe to assume that organic compounds that might have contributed to the prebiotic potential of the planet could have been synthesized elsewhere in the solar system or in interstellar space and then carried to the surface of Mars via carbonaceous chondrites and interplanetary dust particles. Since there is no consensus about the past history of prebiotic processes on Mars, it is more constructive to first consider the availability of the elements that constitute organic matter.

- *Carbon.* C is found as gaseous carbon dioxide in the martian atmosphere, as carbon dioxide ice, and as carbonate minerals. Carbonates have been found in small amounts in martian meteorites but have not been detected in significant quantities by orbital remote sensing techniques or in chemical analyses of the martian regolith by landers.
- *Hydrogen.* H is present as water ice and vapor and in hydrated minerals, and may be present within the crust as liquid water. The high D/H ratios of martian water show that Mars has lost a fraction of its water to space from the upper atmosphere. Because of the low atmospheric pressure, liquid water is not stable at the surface of modern Mars. The polar ice caps are thought to contain significant quantities of water ice, and the Gamma Ray Spectrometer on the Mars Odyssey spacecraft has detected significant quantities of subsurface hydrogen, presumably in the form of water ice.[10] Thus, the abundance of hydrogen would not have hindered life on Mars at any time in its history.
- *Nitrogen.* N is poorly retained by the inner planets owing to its volatility and stability as N_2 and also to the relative instability and solubility of its involatile forms. Currently, 2.7 percent of the martian atmosphere is nitrogen. Although nitrogen is crucial for life, it may be rare on Mars.[11] The observed ratio of $^{15}N/^{14}N$ suggests that a large fraction of the planet's nitrogen inventory has been lost to space. No measurements have yet identified nitrogen stored in surface or subsurface minerals.
- *Oxygen.* O is present in H_2O and CO_2, in oxides and sulfate minerals on the highly oxidized surface, and in silicates and other minerals within the crust.
- *Phosphorus.* Phosphate minerals are actually more abundant in meteorites than in most igneous rocks on Earth. Volatile compounds of phosphorus (phosphorus pentoxide and phosphine) are rare, making phosphate minerals more valuable as sources of phosphorus for organisms than other biotic elements with common volatile forms.

- *Sulfur.* S is very abundant as sulfates at the martian surface, and sulfides are common accessory minerals in martian meteorites and, presumably, the martian crust. Isotopic measurements suggest that sulfur species are also present in the martian atmosphere.[12]
- *Other metals.* Metal ions such as are required by biological systems—Mg, Ca, Na, K, and transition elements—are abundant in martian surface rocks and, presumably, in subsurface rocks as well.

TERRAN BIOSIGNATURES AND POTENTIAL MARTIAN BIOSIGNATURES

Molecular Biosignatures

The carbon chemistry of terran organisms is well understood. Researchers have detailed knowledge of the metabolic and reproductive machinery of many living organisms and can recognize the residual chemicals long after life has expired. Chemistry provides many tools for identifying extant and fossil carbon-based life on Earth and, potentially, throughout the universe.

At the most basic level, researchers can examine the elemental composition of bulk organic matter preserved on Mars or in returned Mars samples as an indicator of biogenicity. On Earth, all organisms are composed largely of the six elements—C, H, N, O, P, and S—whose abundances are discussed above and in Chapter 2. Their proportions vary between organisms and ecosystems.[13] Mechanisms and pathways involved in preservation can change these ratios; for example, N and P decline significantly during fossilization. Nevertheless, the discovery in a Mars sediment sample of organic matter with significant abundances of N, O, P, and S would indicate a similarity to biological material on Earth. The relative scarcity of N (see previous section) combined with the key role it plays in biological processes suggests that organic nitrogen compounds would be an important potential biosignature.[14]

Organic geochemists coined the term "biological marker compound" or "biomarker" to describe individual organic compounds that serve as molecular biosignatures.[15–17] Biomarkers comprise a spectrum of biomolecules spanning those that are present in living systems (biomarkers for extant life), structurally-related fossil derivatives that have been preserved in sediments (biomarkers for past life), or complex chemicals that have generic traits characteristic of biology but for which no precursor organism is known (sometimes called orphan biomarkers). The last set could include molecules derived from unrecognized terran life (present or past) or extraterrestrial life.

Biomolecules commonly show a huge diversity of chemical structures. However, unambiguous identification of something as chemically complex and biology-specific as DNA, a protein, a phospholipid, a steroid, or even a select set of small molecules would be difficult to refute as a successful life-detection experiment. Such a set of select small molecules might include some of the 20 protein amino acids in large excess over their nonprotein counterparts, some sugars, or a select group of fatty acids such as might be found in the polar lipids of contemporary organisms. While nucleic acids, proteins, carbohydrates, and intermediary metabolites are essential components of life, and obviously potential molecular biosignatures, compounds in these classes are rapidly recycled by other living systems and are chemically fragile. On Earth, they are not known for their ability to survive intact over geological timescales.

Lipids and structural biopolymers are biologically essential classes of compounds renowned for their stability under harsh environmental conditions.[18] Hydrocarbons, for example, are a class of lipid known to be stable on Earth over billion-year timescales.[19,20] Furthermore, their chemical structures can be as diagnostic for biology as those of amino acids or other biomolecules. Thermodynamic arguments suggest that the lower temperatures on Mars would aid in the preservation of hydrocarbons. The specific empirical evidence for this comes from observations of petroleum deposits on Earth: high-temperature reservoirs show enhanced hydrocarbon cracking (i.e., more gas and gasoline-grade hydrocarbons) compared to equivalent low-temperature reservoirs.

Several important molecular biosignatures result from the propensity of molecules containing just a few carbon atoms to exist in different chemical and structural configurations, known as isomers. In other words, isomers are molecules having the same number of atoms of each element (i.e., their chemical formulas are the same), but exhibiting different connectivities between, and/or spatial arrangements of, their constituent atoms. In the simplest of cases, isomers of the same compound might be chemically identical but differ in their ability to rotate polarized light (e.g., the chirality of amino acids, as described in Box 3.1). In more complex examples, the connectivity and spatial arrangements of atoms in organic molecules might give rise to compounds with very different chemical and physical characteristics (e.g., the diastereoisomers and structural isomers described in Boxes 3.2 and 3.3, respectively). All of these properties can unambiguously indicate biological origins because living systems frequently make use of just one of the multiple isomers that can exist for any given molecule.[21,22]

Another important set of molecular biosignatures can be identified, based on the observation that all known organisms utilize a universal subset of small metabolites as generic building blocks for constructing biomass and more complex biomolecules.[23] The 20 amino acids of proteins, the four nucleotides of DNA, and the acetate precursor of most lipids are prime examples of generic building blocks. This simple fact, so fundamental to life on Earth, leads to patterns in the molecules of life and in the molecular remains of past life. This is in stark contrast to organic compounds produced in abiotic processes, which have structures and distributions with distinctly different patterns more likely to reflect thermodynamic controls. For any class of organic compounds, biosynthesis results in recurring patterns, readily recognizable to organic chemists. Detection of particular patterns (e.g., biomolecules with a preference for even or odd numbers of carbon atoms, as described in Box 3.4) and recurring themes (e.g., families of related molecules with a limited subset of all the possible numbers of carbon atoms, as described in Box 3.5) in small to moderate-sized organic molecules could lead to the validation of biosignatures for both terran and, possibly, nonterran life.

Taken together, these various chemical characteristics have led researchers to identify the following generic molecular biosignatures for carbon-based life:

- Chirality (see Box 3.1),
- Diastereoisomeric preference (see Box 3.2),
- Structural isomer preference (see Box 3.3),
- Repeating structural subunits or atomic ratios (see Box 3.4), and
- Uneven distribution patterns or clusters of structurally related compounds (see Box 3.5).

In summary, any family of organic molecules common to Earthly life (e.g., lipids) if discovered on Mars would be important biological markers. However, at a more basic level, patterns of carbon number, or limited isomer distributions, or, isotopic composition (see next section), consistent with synthesis from small, repeating precursor molecules may point the way to the detection of extraterrestrial life be it terran or non-terran in its biological architecture.

Isotopic Biosignatures

The elements that are most important in organic chemistry all have multiple isotopes. The isotopic patterns of these elements and, increasingly, of transition metals can constitute biosignatures in terran samples. This is the case because kinetically controlled isotopic fractionations are common in biology and can be significant and dominant over equilibrium fractionation. Although geological processes fractionate these isotopes, biological processes tend to produce different, and sometimes diagnostic, effects. For example, enzymes involved in carbon fixation, methanogenesis, methane oxidation, sulfate reduction, and denitrification impose significant fractionations between precursor and product for carbon, hydrogen, sulfur, and nitrogen. Depletions or enrichments of certain isotopes from expected values can be used as biosignatures. However, such fractionations can reveal biological activity only if all the various components of a system are available for measurement and open system behavior has operated.

No fractionations will be observed if all of a precursor is converted to a product, regardless of whether equilibrium or kinetic fractionations operate. Furthermore, for an isotopic biosignature to be sound, the components of the system must be preserved intact without subsequent fractionation by physical or chemical processes. A myth commonly perpetuated is that a C-isotopic signature in organic carbon compounds of –20‰ to –80‰ is diagnostic of biology irrespective of any other factor. The ^{13}C-composition in organic compounds can be a biosignature only if the isotopic composition of the precursor carbon source is also known and, importantly, if the pedigree of the materials is also consistent with biological processes. These issues have made biological interpretations of

BOX 3.1
Chirality

An important property of carbon compounds is that the same atoms can bond to each other in the same manner while assuming different configurations in space. The different three-dimensional arrangements of organic molecules having the same chemical and structural formulas can lead to a number of important properties relevant to the study of biomarkers. One of these properties is chirality. That is, some molecules have their component atoms arranged in two different spatial configurations that are mirror images of each other. If the mirror images are not superimposable one upon the other, then the molecule is said to be chiral and its two structural forms are called enantiomers (Figure 3.1.1).

The vast preponderance of biologically formed chiral compounds are synthesized exclusively as one or the other enantiomer; for example, right-handed sugars and left-handed amino acids are the norm in biological systems. This phenomenon is known as homochirality. Some organisms, bacteria for example, may synthesize the same chiral compound in different enantiomeric forms. Once the organism dies, and its biochemicals are released into the environment, their chiral purity may or may not persist depending on the relative stability of the chemical bonds in the enantiomers. Various natural chemical processes can lead to racemization, the formation of mixtures of the two enantiomers. Although racemization may result in loss or corruption of a biological signature, the rate at which it happens can also have a practical application, such as in the dating of fossil organic matter using the degree of amino acid racemization. Amino acids with a slight chiral excess of, presumably, abiotic origin occur in meteorites.[1,2] Nevertheless, biology is the most likely source of compounds that occur purely or predominantly as one enantiomer.

Enantiomeric excess can be detected in a number of ways. Chiral compounds are optically active. That is, they rotate the plane of polarized light passing through them when in solution. Direct observation of optical activity is cumbersome. Biochemical detection of enantiomeric excess is possible, but the methodologies are generally specific to individual compounds or compound types. The most widely applicable and sensitive techniques involve indirect measurement through gas chromatography or gas chromatography-mass spectrometry.

---

[1]J.R. Cronin and S. Pizzarello, “Enantiomeric Excesses in Meteoritic Amino Acids,” *Science* 275:951-955, 1997.

[2]M.H. Engel and S.A. Macko, eds., *Organic Geochemistry Principles and Applications*, Plenum Press, New York, 1993.

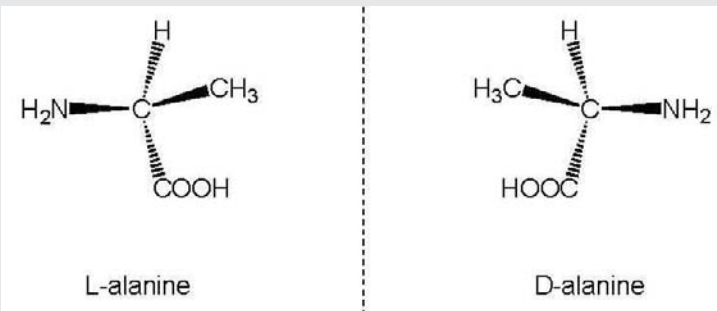


FIGURE 3.1.1 The atoms in the α-amino acid alanine can assume two different configurations in three-dimensional space. The two forms, L-alanine and D-alanine, are called enantiomers because they are non-superimposable mirror images of each other. Abiotic processes produce equal mixtures of both L and D enantiomers, but terran life preferentially uses the L or D form. For example, most organisms on Earth make exclusive use of the L form of α-amino acids. Chemical bonds oriented out of and into the plane of the page are shown as solid or dashed wedges, respectively. Courtesy of Roger E. Summons, Massachusetts Institute of Technology.

BOX 3.2
Diastereomeric Preference

Diastereomeric preference is another manifestation of the ability of atoms in certain molecules to assume different orientations in space. If the two spatial arrangements of atoms are not mirror images of each other, then the different molecular forms are known as diastereomers or diastereoisomers (Figure 3.2.1). Unlike enantiomers, diastereoisomers have different physical and chemical properties and can be separated by chromatography or other processes that exploit subtle differences in polarity. Simple sugars are good examples of diastereoisomers and the more complex the molecule, the more possibilities there are to form diastereomers. Thus, for example, the steroid cholesterol (see Figure 3.2.2) can exist in 256 different structural configurations, but living systems make use of only one of them.[1]

[1]K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, 2004.

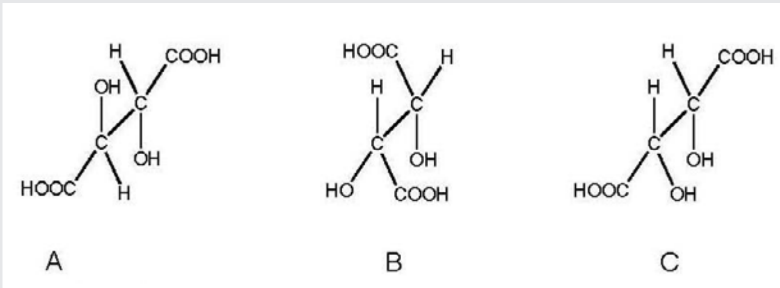


FIGURE 3.2.1 The ability of atoms in organic molecules to assume multiple configurations in three-dimensional space is demonstrated by these three forms of tartaric acid. Structures A and B and A and C are superimposable mirror images of each other and so are termed diastereomers. Structures B and C are non-superimposable mirror images of each other and are, thus, enantiomers (see Box 3.1). Courtesy of Roger E. Summons, Massachusetts Institute of Technology.

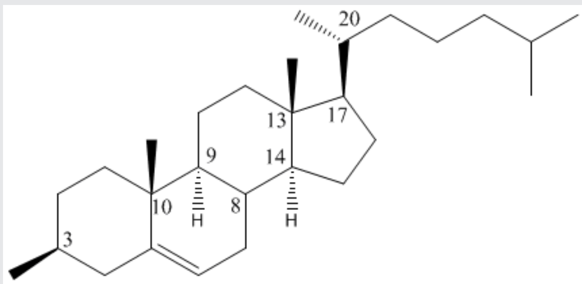


FIGURE 3.2.2 Structure of cholesterol with its eight asymmetric carbon atoms identified with their position number. Theoretically, this compound could exist in as many as 256 (2^8) possible stereoisomers, and yet biosynthesis produces only the one illustrated.

carbon, nitrogen, or sulfur isotopic data in Archean sediments, for example, subject to debate.[24–27] Although not likely to yield unambiguous biosignatures in the near future, isotopic analyses of martian sediments and atmospheric gases will be important for discerning their evolution and for establishing comparative data, as they do on Earth. Identification of a suite of supporting isotopic data in a reaction pathway, and its environmental context, is the most effective approach to identifying an isotopic biosignature. Elucidation of the isotopic systematics of

BOX 3.3
Structural Isomers

The propensity of carbon compounds to exist with multiple ring systems and unsaturations means that the generic organic compound $C_pH_qN_rO_sP_tS_u$, can assume an enormous variety of possible structures, known as structural isomers.[1] Despite the potential for variety, researchers observe that naturally synthesized biochemicals fall into patterns, and the number of known compounds is but a small subset of what is chemically feasible. Moreover, the biomolecule may be the thermodynamically least favored structure within a set of possible isomers if this aspect enhances its functional capacity.

Structural isomers are readily separated using chromatography. In many, but not all cases, their mass spectra are also distinctive. As with other forms of isomerism, combinatorial instruments such as gas chromatographs-mass spectrometers and liquid chromatographs-mass spectrometers provide the most sensitive and diagnostic tools for trace analysis.

[1]E.L. Eliel, S.H. Wilen, and L.N. Mander, *Stereochemistry of Organic Compounds*, Wiley, New York, 1994.

the C-cycle on Earth has been underway for more than 50 years, and much remains to be understood.[28,29] An added complication for studies of Mars is the unknown degree to which nonbiological atmospheric processes fractionate isotopes.

An example of an isotopic biomarker that might be used in the search for life on Mars is the $^{18}O/^{16}O$ ratio in phosphates.[30] Phosphorus in the form of phosphates (PO_4^{3-}) is utilized in genetic material and cell membranes, and as a cofactor and energy-transporting molecule in terran biology. On Earth, the ultimate source of PO_4^{3-} is apatite that is dissolved, biologically processed, and redeposited as various sedimentary PO_4^{3-} phases and as biogenic calcium phosphate deposits (phosphorites). Biologically processed PO_4^{3-} on Earth has a strong biotic O-isotopic signature that is highly evolved from abiotic apatite baseline values. On Mars, evolution of the $^{18}O/^{16}O$ ratios in phosphates from this abiotic baseline could be used as a biomarker. Furthermore, the $^{18}O/^{16}O$ ratio of PO_4^{3-} records temperature and high-temperature exchange reactions with water, also making PO_4^{3-} a potential indicator of past hydrothermal activity on Mars.[31]

An additional example of an isotopic effect concerns the tendency in biological processes for large molecules to be synthesized by the repeated addition of subunits of two or five carbon atoms (see Box 3.4). The lipid building blocks acetate (C_2) and isopentenyl pyrolphosphate (C_5) are, for example, isotopically inhomogeneous. Acetate provides one of the best examples because it shows very significant differences in the ^{13}C contents of its methyl and carboxyl carbons.[32] The most overt consequences are isotopic ordering in fatty acids and a major isotopic difference between acetogenic and polyisoprenoid lipids. In a single organism, the isotopic differences between acetogenic and polyisoprenoid lipids depend on how many of the polyisoprenoid carbon atoms arise from acetate versus carbohydrate metabolism.[33]

Morphological Biosignatures

Morphological biosignatures represent the class of objects that can be interpreted as indicative of life based on their size, shape distribution, and provenance. Features of interest occur at both the macroscopic (e.g., stromatolites and microbially induced sedimentary structures) and the microscopic (e.g., microfossils) scale. If they were discovered on Mars, macroscale morphological features such as stromatolites, although being the subject of some contention as a definitive indicator of biogenicity,[34] would prove to be highly desirable targets for further study and/or sample return.[35–37]

BOX 3.4
Subunits and Building Blocks of Complex Organic Molecules

Virtually all biomolecules are constructed from a limited number of generic subunits or building blocks, the best-known examples being proteins and nucleic acids. Lipids, which are formed from only two basic building blocks, are polymers of either acetate or isopentenyldiphosphate precursors. The final products lack a hydrolyzable functionality (e.g., peptide linkages) at the point where subunits join, and, unlike other proteins and nucleic acids, lipids cannot be depolymerized.

A classic example of lipids are those that are found in membrane lipid bilayers of bacteria and eukarya and are made up of fatty acids esterified to glycerol. The most common fatty acids are all-acetate products and thus have even carbon numbers (e.g., C_{14}, C_{16}, C_{18}, and C_{20}). Odd-carbon-numbered members, generally synthesized from a non-acetyl starter, exist but are less abundant. Extension of fatty acid chain length proceeds by the addition of further acetate units. Terminating and modifying reactions such as desaturation, reduction, or decarboxylation yield common intermediate-molecular-weight series of products such as the plant and algal waxes made up of even-numbered alcohols (e.g., C_{26}, C_{28}, C_{30}, C_{32}) and odd-numbered hydrocarbons (e.g., C_{25}, C_{27}, C_{29}, C_{31}).

An additional illustration of the building-block principle is displayed by the terpenoids. These polymers of Δ3-isopentenyldiphosphate have somewhat more complex origins and much more complex structures (Figure 3.4.1). As a result of isoprenoid biosynthesis and its evolution over geological time, terran life contains an enormous array of complex molecules related through their C_5 architecture. The multiplicity of isoprenoid biosynthetic pathways, their distribution across different phylogenetic groups, their requirement, or otherwise, for molecular oxygen, and the types of post-synthesis modification are generally held to provide a powerful biosignature of evolutionary origins. For example, the molecules resulting from the pathway shown in Figure 3.4.1 are highly diagnostic of biosynthesis because, individually, they exhibit many features of biosynthesis (e.g., carbon number, chirality, and subsets of isomers).

Crocetane, 2,6,10-trimethyl-7-(3-methylbutyl)-dodecane, squalene, and biphytane are irregularly branched compounds, whereas phytane, labdane, and kaurane are regular and are constructed from four head-tail linked isoprene units. These compounds also illustrate how different structures can be diagnostic for specific physiologies (phytol and farnesol for photosynthesis, phytane for various archaea, crocetane for methanotrophy) or specific organisms (2,6,10-trimethyl-7-(3-methylbutyl)-dodecane for diatoms; biphytane for crenarchaeota; labdane and kaurane for conifers).

---

[1]G. Ourisson and P. Albrecht, "Hopanoids. 1. Geohopanoids: The Most Abundant Natural Products on Earth?," *Accounts of Chemical Research* 25:398-402, 1992.

Cameras and spectral imagers on previous, continuing, and planned life-detection missions to Mars are capable of identifying structures and objects ranging from the macroscopic to the minuscule that, on Earth, are considered visible signatures for past or present biological activity. Such objects and structures include intact microbes, metazoa and metaphytes, stromatolites, microbial mats, and other large-scale structures composed of aggregates of cells, as well as component parts of multicellular organisms such as cysts, pollen, embryos, organs, and so on. On Earth, these objects are pervasive in surface environments and in the deep subsurface and leave no doubt about how abundant and tenacious life is. Researchers can also, to a degree, visually identify in Earth's sediments a rich fossil life extending in age to more than 2 billion years. So far, no such visible "biological" objects have been convincingly identified on Mars or in martian meteorites. If life exists, or existed in the past, on Mars or other

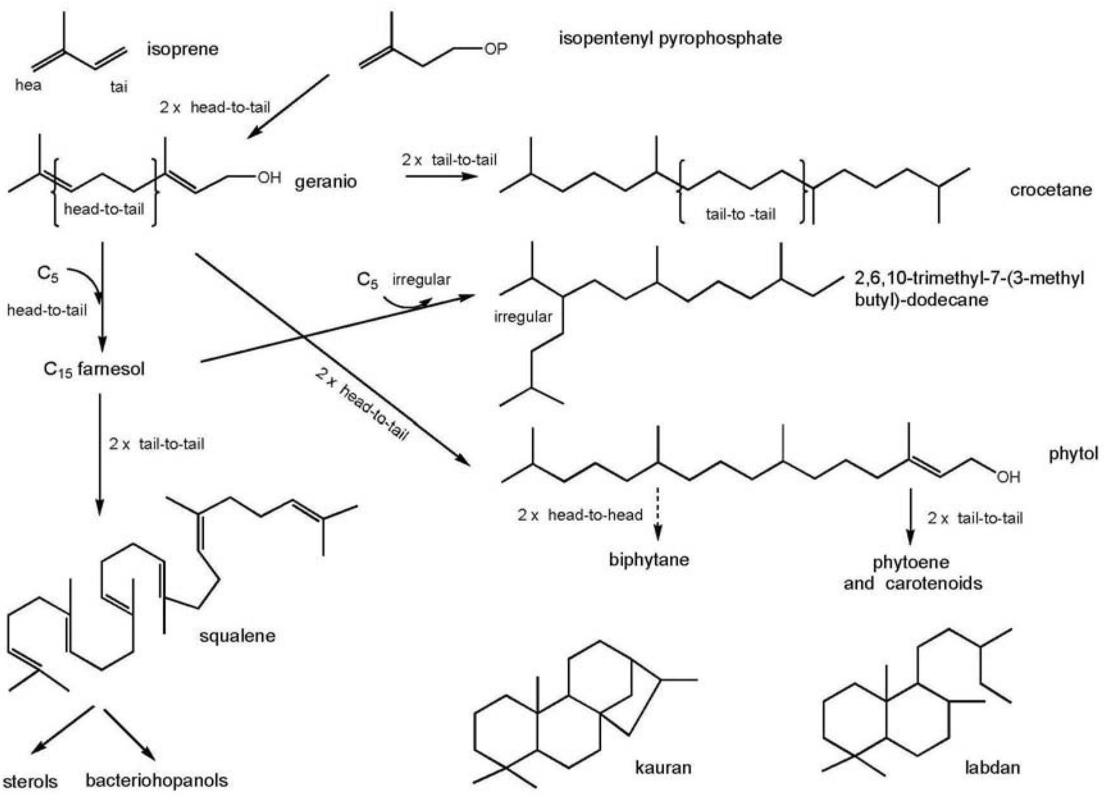


FIGURE 3.4.1 Structures of some regular, irregular, and cyclic C_2O (diterpenoid) and C_3O (triterpenopid), and C_4O (tetraterpenoid) hydrocarbons that have been identified in sediments and that illustrate a variety of biosynthetic patterns based on repeating five-carbon subunits (after J.M. Hayes, "Fractionation of Carbon and Hydrogen Isotopes in Biosynthetic Processes," *Reviews in Mineralogy and Geochemistry* 43: 225-277, 2001).

planetary bodies, the evidence has not been forthcoming. In many respects, the search for martian life mirrors the search for the earliest life on Earth and faces similar obstacles. Attempting to reconstruct terran life's history back into deep time, researchers are confronted by the problem of a record made increasingly cryptic by the geochemical and geological processes that continually re-surface Earth and modify the rock record.

Poor preservation and ambiguity about what constitutes a biosignature have confounded the search for visible evidence of early microbial life on Earth[38–45] and in the martian meteorite ALH 84001 in particular.[46] Related reports, and some of the controversies stemming from them, teach researchers that drawing an inference of biogenicity based on morphology is fraught with difficulties. If the feature being observed is demonstrably syngenetic with the host rock and displays a limited size (length and width) distribution, shows evidence of cellular

BOX 3.5
Clusters and Uneven Distribution Patterns of Structurally Related Compounds

The biosynthesis of large organic molecules from smaller molecules, as discussed in Box 3.4, leads to wider consequences, evidence of which can, in principle, be used as biomarkers. The synthesis of lipids by organisms, for example, from C_2 or C_5 building blocks creates clusters of compounds that differ by *n* C_2 (acetogenic lipids) or *n* C_5 (polyisoprenoids) units, where *n* is a positive interger. In a typical sample of terrestrial lipids, researchers find, for example, a predominance of even-carbon-numbered fatty acids; odd-carbon-numbered hydrocarbons in leaf wax; C_{15}, C_{20}, and C_{25} acyclic isoprenoids; C_{20} and C_{30} cyclic terpenoids including steroids; and C_{40} carotenoids. Subsets of these traits are even identifiable in highly altered or processed materials such as petroleum, where *n*-alkanes may exhibit preferences for odd-over-even or even-over-odd carbon numbers. Clusters of carbon numbers have the potential to be biosignatures because they indicate biosynthesis from universal building blocks.

In addition to obvious patterns of related compounds differing by two or five carbon atoms, the action of repeated addition of C_2 or C_5 subunits leads to an additional important biosignature. Functional biochemicals, such as lipids, have a tendency to show clusterings of related compounds at discrete molecular weight ranges. Examples of clusters seen include the following:

- C_{14}-C_{20} for fatty acids;
- C_{15}-C_{17} and C_{25}-C_{33}, respectively, for hydrocarbons associated with, for example, bacteria and plants;
- C_{26}-C_{30} for the sterols associated with most eukaryotes;
- C_{30} for the triterpenoids associated with plants and bacteria; and
- C_{20}, C_{25}, C_{30}, and C_{40} for lipids associated with archaea.

An additional biomarker related to clustering and isotopic fractionation is described in the subsection "Isotopic Biosignatures."

A factor complicating the use of these biosignatures is the fact that most samples of biologically produced organic matter come from organisms that exist in complex ecosystems. The volatile components of a microbial mat, for example, will show compound classes with carbon numbers distributed roughly as described above and in Box 3.4. Similarly, the lipids in biofilms from hydrothermal vents display an uneven-carbon-number distribution.[1] The geological record is replete with additional examples.[2] Moreover, the C_{25}-C_{30} fraction might contain more material than the C_{15}-C_{20} fraction. This "lumpiness" is in stark contrast to what is seen in assemblages of molecules made abiotically.[3,4] The Fischer-Tropsch process used to synthesize hydrocarbons, for example, creates molecules with an exponential distribution of sizes, with $C_1 > C_2 > C_3 > C_4$, and so on, falling away to almost zero by C_{30}. Similarly, the amino acids seen in meteorites exhibit more C_1 than C_2 than C_3 than C_4 and so on.[5-8]

---

[1]L.L. Jahnke, W. Eder, R. Huber, J.M. Hope, K.U. Hinrichs, J.M. Hayes, D.J. Des Marais, S.L. Cady, and R.E. Summons, "Signature Lipids and Stable Carbon Isotope Analyses of Octopus Spring Hyperthermophilic Communities Compared to those of Aquificales Representatives," *Applied and Environmental Microbiology* 67:5179-5189, 2001.

[2]K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, U.K., 2004.

[3]See, for example, B. Sherwood Lollar, T.D. Westgate, J.A. Ward, G.F. Slater, and G. Lacrampe-Couloume, "Abiogenic Formation of Alkanes in the Earth's Crust as a Minor Source for Global Hydrocarbon Reservoirs," *Nature* 416:522-524, 2002.

[4]See, for example, M. Allen, B. Sherwood-Lollar, B. Runnegar, D.Z. Oehler, J.R. Lyons, C.E. Manning, and M.E. Summers, "Is Mars Alive?," *Eos* 87:433 and 439, 2006.

[5]M.A. Sephton, "Organic Compounds in Carbonaceous Meteorites," *Natural Products Reports* 19:292-311, 2002.

[6]M.A. Sephton, C.T. Pillinger, and I. Gilmour, "Aromatic Moieties in Meteoritic Macromolecular Materials: Analyses by Hydrous Pyrolysis and 13 C of Individual Compounds," *Geochimica et Cosmochimica Acta* 64:321-328, 2000.

[7]M.A. Sephton, C.T. Pillinger, and I. Gilmour "Pyrolysis-Gas Chromatography–Isotope Ratio Mass Spectrometry of Macromolecular Material in Meteorites," *Planetary Space Science* 47:181-187, 2001.

[8]M.A. Sephton, G.D. Love, J.S. Watson, A.B. Verchovsky, I.P. Wright, C.E. Snape, and I. Gilmour, "Hydropyrolysis of Insoluble Carbonaceous Matter in the Murchison Meteorite: New Insights into Its Macromolecular Structure." *Geochimica et Cosmochimica Acta* 68:1385-1393, 2004.

degradation, or is part of a discernable population that occurs in discrete phases within the samples on Earth that are relevant to the context of the sample, then further investigation is warranted.[47] The debates on early life and ALH 84001 (see Chapter 2) have shown that morphology must be combined with both chemistry and context to enable unambiguous detection of life. However, morphology is extremely valuable for detecting targets of interest for further investigation, particularly macroscopic structures such as stromatolites, microbial mats, and other large-scale aggregates created by communities of microorganisms.

Mineralogical and Inorganic Chemical Biosignatures

The mineralogy and chemistry of Earth materials can constitute a biosignature in some systems where organisms either accelerate or inhibit reactions that are thermodynamically possible. In addition, organisms can change the chemistry of rocks, fluids, and gases through the processes of secretion, assimilation, and electron transfer, sometimes creating mineralogical or chemical gradients that differ from those that would be established in an abiotic environment. Although there are a few examples of mineralogical biosignatures on Earth that unambiguously identify a biotic origin (e.g., coccoliths and diatoms), these are not likely to be applicable to Mars.[48] Most other types of inorganic chemical biosignatures can provide only indirect evidence of the presence of life and would thus most likely constitute supporting evidence accompanying other more diagnostic criteria. Examples of inorganic biosignatures are discussed below.

Biota can affect the identity of phases manifested in the rock record. For example, some bacteria transform mackinawite to greigite (sulfides),[49] and some fungi promote the formation of weddellite (Ca oxalate) in soils. These effects are related to the biological ability to nucleate minerals onto organic templates, or to the production of organic ligands that solubilize elements, affect growth mechanisms, or precipitate as salts. The inclusion of organic molecules or micronutrient impurities in mineral precipitates could also conceivably be indicative of biological activity.

Physical properties of minerals might also yield indirect, albeit ambiguous, evidence of biological processes. For example, the size distribution of precipitates might indirectly suggest a biotic origin, given that many mineralogical by-products of metabolism are nanocrystalline because they are formed under conditions of high oversaturation.[50] Surface etching or crystal habit, which can be affected by biological exudates or biofilm formation, might also be indirect indicators of biota. Biological phenomena can also be inferred in some cases from the characteristics of aggregations of minerals. Of possible interest for Mars is aggregation characteristic of Fe minerals precipitated by bacteria. For example, both the size distribution and the aggregation of magnetite crystals have been posited as biosignatures,[51,52] although these characteristics have also been attributed to abiotic processes,[53] thus pointing out the ambiguous nature of mineralogical properties as biosignatures.

Gradients in the concentration of elements recorded in Earth materials can also be diagnostic of biological phenomena. A well-known manifestation of elemental gradients driven by biological processes is certain soil horizons in which the exudation of organic complexants mobilizes elements and produces patterns indicative of the presence of biota.[54] The formation of gradients in the concentration of elements at the meter scale in soil horizons and at the micron scale on mineral surfaces or in endolithic communities might thus be important.[55–57] The assimilation of trace elements at a low concentration by microorganisms or the sequestration of toxic elements into biologically mediated precipitates could also create distributions of trace elements that record the prior presence of biota in regolith or sedimentary environments.

Anomalies in the concentration of phosphorus have also been suggested as possible biomarkers that could be used in the search for life on Mars.[58] Phosphorus as PO_4^{3-} is utilized in a wide variety of biological processes and material. The ultimate source of PO_4^{3-} on Earth is igneous apatite, which is biologically processed and redeposited as biogenic calcium phosphates (phosphorites). On Earth, PO_4^{3-} is adsorbed strongly to iron- and aluminum-oxides and oxyhydroxides under aqueous conditions. Phosphorus phases found in martian soils, sedimentary environments, and in association with the abundant iron oxides on Mars might be a good target in a search for phosphorus as a biosignature. Additionally, patterns of phosphorous concentration could be used to guide the search for potential PO_4^{3-} biosignatures and other kinds of fossils.

Based on such considerations, past and present approaches to Mars astrobiological exploration have heavily emphasized instrument packages capable of detecting the chemical signatures of life, especially carbon compounds, isotopic signatures, and various other products of metabolism. The 2001 workshop on biosignatures organized by the NASA Biomarker Task Force established comprehensive objectives for developing a better understanding of biosignatures. Unfortunately, though, the results of the task group's deliberations were never published in full.[59] Because they represent an important starting point for future discussions, those objectives are reproduced in Appendix C.

REFERENCES

1. J.J. Brocks and R.E. Summons, "Sedimentary Hydrocarbons, Biomarkers for Early Life," pp. 65-115 in *Treatise in Geochemistry* (H.D. Holland and K. Turekian, eds.), 2003; K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, 2004.

2. See, for example, A.H. Knoll, R.E. Summons, J.R. Waldbauer and J.E. Zumberge, "Successions in Biological Primary Productivity in the Oceans" in *The Evolution of Photosynthetic Organisms in the Oceans* (P. Falkwoski and A.H. Knoll eds), in press; K.E. Peters, J.M. Moldowan and C.C Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, 2004.

3. See, for example, A.I. Rushdi and B.R.T. Simoneit, "Lipid Formation by Aqueous Fischer-Tropsch-Type Synthesis over a Temperature Range of 100 to 400°C," *Origins of Life and Evolution of Biospheres* 31:103-118, 2004; J.D. Pasteris and B. Wopenka, "Laser–Raman Spectroscopy (Communication Arising): Images of the Earth's Earliest Fossils?" *Nature* 420:476-477, 2002; B. Sherwood Lollar, T.D. Westgate, J.A. Ward, G.F. Slater, and G. Lacrampe-Couloume, "Abiogenic Formation of Alkanes in the Earth's Crust as a Minor Source for Global Hydrocarbon Reservoirs," *Nature* 416:522-524, 2002; T.M. McCollom, and J.S. Seewald, "Carbon Isotope Composition of Organic Compounds Produced by Abiotic Synthesis under Hydrothermal Conditions," *Earth and Planetary Science Letters* 243:74-84, 2006.

4. S.L. Miller, "Production of Some Organic Compounds under Possible Primitive Earth Conditions, *Journal of the American Chemical Society* 7:2351, 1955.

5. J.A. Kasting, "Bolide Impacts and the Oxidation State of Carbon in the Earth's Early Atmosphere," *Origins of Life and Evolution of the Biosphere* 20:199-231, 1990.

6. See, for example, R.M. Hazen "Life's Rocky Start," *Scientific American* 284(4):76-85, 2001.

7. J.A. Brandes, N.Z. Boctor, G.D. Cody, B.A. Cooper, R.M. Hazen, and H.S. Yoder, "Abiotic Nitrogen Reduction on the Early Earth," *Nature* 395:365-367, 1998.

8. G. Wächtershäuser, "Before Enzymes and Templates: Theory of Surface Metabolism," *Microbiology Review* 52:452-484, 1988.

9. G. Wächtershäuser, "Evolution of the First Metabolic Cycles," *Proceedings of the National Academy of Sciences* 87:200-204, 1990.

10. W.V. Boynton, W.C. Feldman, S.W. Squyres, T.H. Prettyman, J. Brückner, L.G. Evans, R.C. Reedy, R. Starr, J.R. Arnold, D.M. Drake, P.A.J. Englert, A.E. Metzger, I. Mitrofanov, J.I. Trombka, C. d'Uston, H. Wänke, O. Gasnault, D.K. Hamara, D.M. Janes, R.L. Marcialis, S. Maurice, I. Mikheeva, G.J. Taylor, R. Tokar, and C. Shinohara, "Distribution of Hydrogen in the Near Surface of Mars: Evidence for Subsurface Ice Deposits," *Science* 297:81-85, 2002.

11. D.G. Capone,R. Popa, B. Flood, K.H. Nealson, "Geochemistry. Follow the Nitrogen," *Science* 312:708-709, 2006.

12. J. Farquhar, J. Savarino, T.L. Jackson, M.H. Thiemens, "Evidence of Atmospheric Sulphur in the Martian Regolith from Sulphur Isotopes in Meteorites," *Nature* 404:50-52, 2000.

13. P.G. Falkowski and C.S. Davis, "Natural Proportions," *Nature* 431:131, 2004.

14. D.G. Capone, R. Popa, B. Flood, K.H. Nealson, "Geochemistry. Follow the Nitrogen," *Science* 312:708-709, 2006.

15. G. Eglinton and M. Calvin "Chemical Fossils," *Scientific American* 261:32-43, 1967.

16. M.H. Engel and S.A. Macko, eds., *Organic Geochemistry Principles and Applications*, Plenum Press, New York, 1993.

17. K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, 2004.

18. M.H. Engel and S.A. Macko, eds., *Organic Geochemistry Principles and Applications*, Plenum Press, New York, 1993.

19. J.J. Brocks and R.E. Summons, "Sedimentary Hydrocarbons, Biomarkers for Early Life," pp. 65-115 in *Treatise in Geochemistry* (H.D. Holland and K. Turekian, eds.), 2003.

20. K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, 2004.

21. K.E. Peters, J.M. Moldowan, and C.C. Walters, *The Biomarker Guide*, Cambridge University Press, Cambridge, 2004.

22. E.L. Eliel, S.H. Wilen, and L.N. Mander, *Stereochemistry of Organic Compounds*, Wiley, New York, 1994.

23. See, for example, N.A. Campbell and J.B. Reece, *Biology* (7th edition), Benjamin Cummings, 2004.

24. See, for example, S.J. Mojzsis, G. Arrhenius, K.D. McKeegan, T.M. Harrison, A.P. Nutman, and C.R. Friend, "Evidence for Life on Earth Before 3,800 Million Years Ago," *Nature* 384:55-59, 1996.

25. M.A. van Zuilen, K. Mathew, B. Wopenka, A. Lepland, K. Marti, and G. Arrhenius, "Nitrogen and Argon Isotopic Signatures in Graphite from the 3.8-Ga-old Isua Supracrustal Belt, Southern West Greenland," *Geochimica et Cosmochimica Acta* 69:1241-1252, 2005.

26. Y. Ueno, H. Yurimoto, H. Yoshioka, T. Komiya, and S. Maruyama, "Ion Microprobe Analysis of Graphite from ca. 3.8 Ga Metasediments, Isua Supracrustal Belt, West Greenland: Relationship between Metamorphism and Carbon Isotopic Composition," *Geochimica et Cosmochimica Acta* 66:1257-1268, 2002.

27. Y. Shen, R. Buick and D.E. Canfield "Isotopic Evidence for Microbial Sulphate Reduction in the Early Archaean Era," *Nature* 410:77-81, 2001.

28. H. Craig, "The Geochemistry of the Stable Carbon Isotopes of Carbon," *Geochimica et Cosmochimica Acta* 3:53-92, 1953.

29. J.M. Hayes and J.R. Waldbauer, "The Carbon Cycle and Associated Redox Processes through Time," *Philosophical Transactions of the Royal Society B: Biological Science* 361:931-950, 2006.

30. R.E. Blake, J.C. Alt, and A.M. Martini, "Oxygen Isotope Ratios of PO_4^-: An Inorganic Indicator of Enzymatic Activity and P Metabolism and a New Biomarker in the Search for Life," *Proceedings of the National Academy of Sciences, Astrobiology Special Feature* 98:2148-2153, 2001.

31. R.E. Blake, J.C. Alt, and A.M. Martini, "Oxygen Isotope Ratios of PO_4^-: An Inorganic Indicator of Enzymatic Activity and P Metabolism and a New Biomarker in the Search for Life," *Proceedings of the National Academy of Sciences, Astrobiology Special Feature* 98:2148-2153, 2001.

32. J.M. Hayes, "Fractionation of Carbon and Hydrogen Isotopes in Biosynthetic Processes," *Reviews in Mineralogy and Geochemistry* 43:225-277, 2001.

33. J.M. Hayes, "Fractionation of Carbon and Hydrogen Isotopes in Biosynthetic Processes," *Reviews in Mineralogy and Geochemistry* 43:225-277, 2001.

34. J.M. Garcia-Ruiz, S.T. Hyde, A.M. Carnerup, A.G. Christy, M.J. Van Kranendonk, and N.J. Welham, "Self-Assembled Silica-Carbonate Structures and Detection of Ancient Microfossils," *Science* 302:1194-1197, 2003.

35. H.J. Hofmann, K. Grey, A.H. Hickman, and R. Thorpe, "Origin of 3.45 Ga Coniform Stromatolites in Warrawoona Group, Western Australia," *Geological Society of America Bulletin* 111:1256-1262, 1999.

36. S.L. Cady, J.D. Farmer, J.P. Grotzinger, J.W. Schopf, and A. Steele, "Morphological Biosignatures and the Search for Life on Mars," *Astrobiology* 3:351-368, 2003.

37. A.C. Allwood, M.R. Walter, B.S. Kamber, C.P. Marshall, and I.W. Burch, "Stromatolite Reef from the Early Archaean Era of Australia," *Nature* 441:714-718, 2006.

38. See, for example, D.R. Lowe, "Abiological Origin of Described Stromatolites Older than 3.2 Ga," *Geology* 22:387-390, 1994.

39. J.P. Grotzinger and A.H. Knoll, "Stromatolites in Precambrian Carbonates; Evolutionary Mileposts or Environmental Dipsticks," *Annual Reviews of Earth and Planetary Sciences* 27:313-358, 1999.

40. H.J. Hofmann, K. Grey, A.H. Hickman, and R. Thorpe, "Origin of 3.45 Ga Coniform Stromatolites in Warrawoona Group, Western Australia," *Geological Society of America Bulletin* 111:1256-1262, 1999.

41. M.D. Brasier, O.R. Green, A.P. Jephcoat, A.K. Kleppe, M.J. Van Kranendonk, J.F. Lindsay, A. Steele, and N.V. Grassineau, "Questioning the Evidence for Earth's Oldest Fossils," *Nature* 416:76-81, 2002.

42. J.W. Schopf, "Microfossils of the Early Archaean Apex Chert: New Evidence of the Antiquity of Life," *Science* 260:640-646, 1993.

43. J.W. Schopf, "Are the Oldest Fossils Cyanobacteria?," pp. 23-61 in *Evolution of Microbial Life Society for General Microbiology Symposium 54* (D. McL. Roberts, P. Sharp, G. Alderson, and M. Collins, eds.), Cambridge University Press, Cambridge, 1996.

44. J.W. Schopf, A.B. Kudryavtsev, D.G. Agresti, T.J. Wdowiak, and A.D. Czaja, "Laser Raman Imagery of Earth's Earliest Fossils," *Nature* 416:73-76, 2002.; J.M. Garcia-Ruiz, S.T. Hyde, A.M. Carnerup, V. Christy, M.J. Van Kranendonk, and N.J. Welham, "Self-Assembled Silica-Carbonate Structures and Detection of Ancient Microfossils," *Science* 302:1194-1197, 2003.

45. S.M. Awramik and K. Grey, "Stromatolites: Biogenicity, Biosignatures, and Bioconfusion," pp. 227-235 in *Astrobiology and Planetary Missions* (R. B. Hoover, G.V. Levin, A.Y. Rozanov, G.R. Gladstone, eds.), *Proceedings of the SPIE*, Volume 5906, 2005.

46. D.S. McKay, E.K. Gibson, Jr., K.L. Thomas-Keprt, H. Vali, C.S. Romanek, S.J. Clemett, X.D.F. Chillier, C.R. Maechling, and R.N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH 84001," *Science* 273:924-930, 1996.

47. J.W. Schopf, "The Oldest Fossils and What they Mean," pp. 29-63 in J.W. Schopf (ed.), *Major Events in the History of Life*, Jones and Bartlett Publishers, Boston, Mass., 1992.

48. J.F. Banfield, J.W. Moreau, C.S. Chan, S.A. Welch, and B. Little, "Mineralogical Biosignatures and the Search for Life on Mars," *Astrobiology* 1:447-465, 2001.

49. M.B. McNeil and B. Little, "Mackinawite Formation during Microbial Corrosion," *Journal of Corrosion* 46:599-600, 1990.

50. J.F. Banfield, J.W. Moreau, C.S. Chan, S.A. Welch, and B. Little, "Mineralogical Biosignatures and the Search for Life on Mars," *Astrobiology* 1:447-465, 2001.

51. K.L Thomas-Keprta, D.A. Bazylinski, J.L. Kirschvink, S.J. Clemett, D.S. McKay, S.J. Wentworth, H. Vali, E.K. Gibson, and C.S. Romanek, "Elongated Prismatic Magnetite Crystals in ALH 84001 Carbonate Globules: Potential Martian Magnetofossils," *Geochimica et Cosmochimica Acta* 64:4049-4081, 2000.

52. K.L. Thomas-Keprta, S.J. Clemett, D.A. Bazylinski, J.L. Kirschvink, D.S. McKay, S.J. Wentworth, H. Vali, E.K. Gibson, Jr., M.F. McKay, and C.S. Romanek, "Truncated Hexa-Octahedral Magnetite Crystals in ALH 84001: Presumptive Biosignatures," *Proceedings of the National Academy of Sciences* 98:2164-2169, 2001.

53. See, for example, A.H. Treiman, "Submicron Magnetite Grains and Carbon Compounds in Martian Meteorite ALH 84001: Inorganic, Abiotic Formation by Shock and Thermal Metamorphism," *Astrobiology* 3:369-392, 2003.

54. A. Neaman, J. Chorover, and S.L. Brantley, "Element Mobility Patterns Record Organic Ligands in Soils on Early Earth," *Geology* 33(2):117-120, 2005.

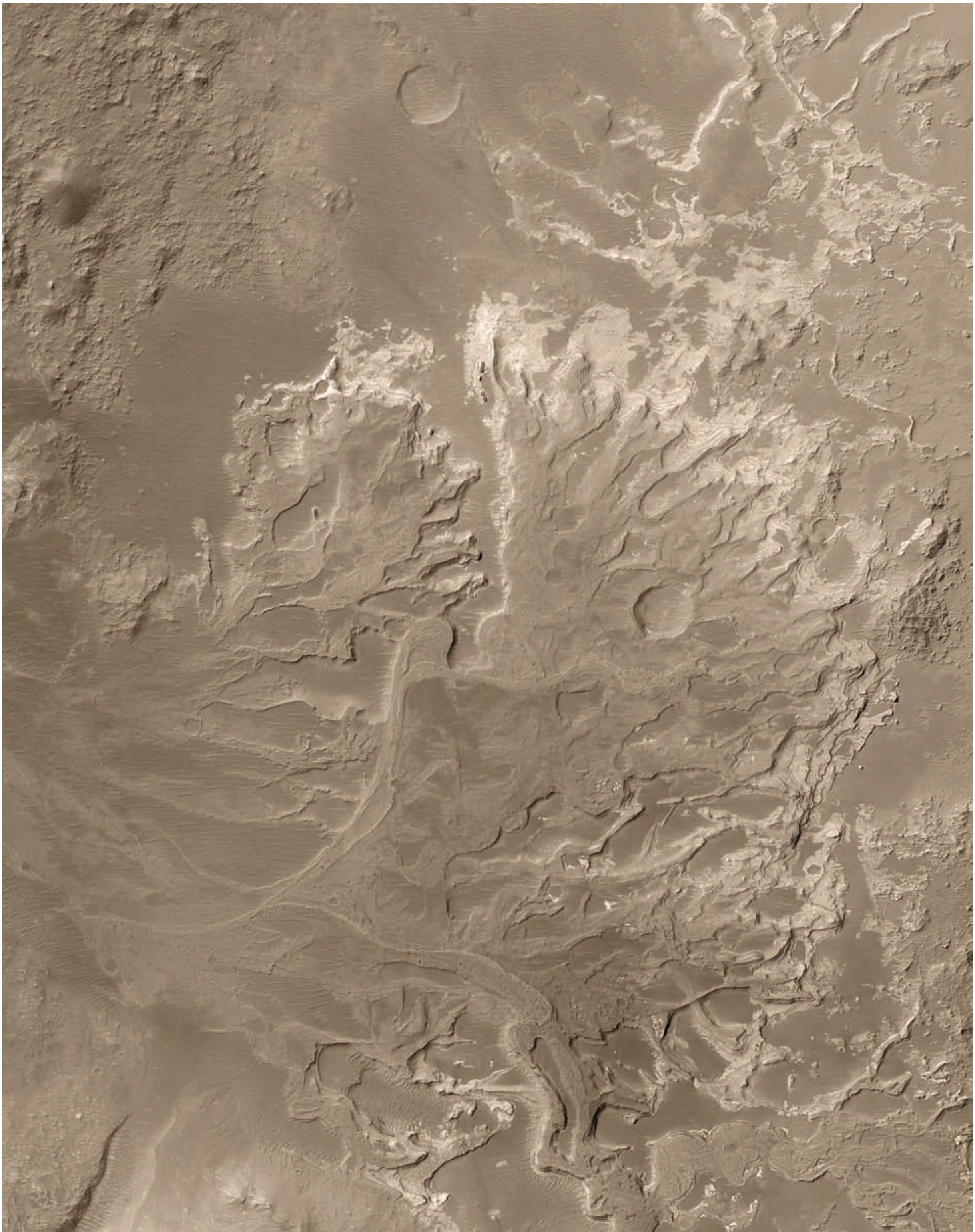
55. B. Kalinowski, L. Liermann, S.L. Brantley, A. Barnes, and C.G. Pantano, "X Ray Photoelectron Evidence for Bacteria-Enhanced Dissolution of Hornblende," *Geochimica et Cosmochimica Acta* 64:1331-1343, 2000.

56. A. Neaman, J. Chorover, and S.L. Brantley, "Element Mobility Patterns Record Organic Ligands in Soils on Early Earth," *Geology* 33(2):117-120, 2005.

57. H.J. Sun and E.I. Friedmann, "Growth on Geological Time Scales in the Antarctic Cryptoendolithic Microbial Community," *Geomicrobiology Journal* 16:193-202, 1999.

58. G. Weckwerth and M. Schidlowski, "Phosphorus as a Potential Guide in the Search for Extinct Life on Mars," *Advances in Space Research* 15:185-191, 1995.

59. Michael Meyer, NASA Science Mission Directorate, personal communication, 2006.



4

Characteristics of Sites for Astrobiological Investigation

Earth is the only planet with irrefutable evidence of life. When Earth formed some 4.55 billion years ago, it was devoid of life, but probably within the first billion years it went through a transition from a planet featuring solely abiotic processes to one featuring both abiotic and biotic processes. This transition did not occur with any certainty on Mars or on any other planetary body. However, astrobiology investigations of Mars seek to determine if life is or ever was present there, and if not, why not. Consequently, astrobiological studies of Mars require investigations that target both abiotic and putative biotic processes (including the possibility that martian life originated elsewhere in the solar system or beyond, as has been suggested by some researchers). Studies of abiotic processes help establish a baseline against which all putative biotic processes can be evaluated. Of particular interest are those abiotic processes that could lead to organic synthesis, polymerization, and the emergence of life—a progression of processes generally called prebiotic chemistry. The focus of this chapter is on the characteristics of sites and samples that are most likely to yield robust evidence of prebiotic chemistry, the preservation of biosignatures from past life, and the existence of present life.

THE SEARCH FOR SIGNS OF PREBIOTIC CHEMISTRY

As noted in Chapter 3, chemistries that may have led to life (prebiotic chemistry) include Miller-Urey type atmospheric electric discharges, serpentinization reactions of Fe-Mg minerals (e.g., olivine), Strecker synthesis, Fischer-Tropsch synthesis, and FeS-driven synthesis. The fundamental step in prebiotic chemistry is the formation of compounds with C-C bonds from single carbon molecules (e.g., CO, CO_2, CH_4). Therefore, the best sites to search for clues about prebiotic chemistry would be those where organic carbon is most likely to be preserved. However, as discussed below, no rich deposits of inorganic carbon have been identified on Mars.

The next section describes those sites that may be the best targets to search for biosignatures of past life, including organic carbon. The proposed target mineralogies and lithologies, which include putative hydrothermal systems, evaporites, sediments, iron oxides, and clay minerals, are the best targets to find possible evidence of

FIGURE 4.1 This delicate fan shape is the product of the long-term distribution of sediments by flowing liquid water. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems. The image covers an area of approximately 8 by 22 km.

prebiotic chemistries. Of these potential sites to preserve biosignatures, the most likely sites are sediments, evaporites, and hydrothermal systems based upon observations of terrestrial rock systems.

THE SEARCH FOR PAST LIFE

The committee approaches a consideration of martian sites from a process-oriented perspective and discusses first the processes most likely to generate and preserve biosignatures. As pointed out in Chapter 3, biosignatures can be molecular, isotopic, morphological, mineralogical, or elemental in nature. This section finishes with a discussion of the characteristics of specific sites where biosignatures of past life might be found.

Processes That May Lead to the Preservation of Biosignatures on Mars

Entombment

Entombment involves processes characterized by rapid mineralization which preserve microorganisms and organic molecules against degradation. Such processes are especially important for reduced compounds preserved in highly oxidizing environments. Examples of processes leading to entombment include the following:

- *Evaporation.* Evaporation leads to mineralization driven by increases in solute concentrations as water is removed. Minerals often crystallize on nuclei provided by microbial cells or organic particles. The relatively rapid precipitation that can occur in evaporative settings often captures particles and compounds within the mineral matrix. In some cases, such entrapped particles can provide evidence of biogenicity.
- *Freezing.* Concentration of brine solutions by freezing is also a likely process of evaporite salt formation and entombment of particles. Its effectiveness as a preservation mechanism may be enhanced by the low temperatures experienced on Mars.
- *Temperature and pressure changes.* Supersaturation due to cooling often leads to precipitation in and around hot springs. Supersaturation can also occur because of changes in pressure. The rate at which precipitation occurs can be rapid enough to entomb living cells or to protect biomolecules. For example, some micro- and macrostructures in and around hot spring deposits show morphological relationships that are uniquely biogenic.[1]

The precipitation that occurs owing to supersaturation can also occur in the subsurface where hydrothermal flow is driven by a buried heat source. The emplacement of igneous intrusives such as dikes infiltrating sedimentary rocks can generate subsurface hydrothermal flow and enhance mineralization reactions. For example, chert, a common authigenic mineral formed by hot springs in igneous terrains, can often preserve biosignatures.

- *Diffusion-driven reactions.* Concretions are precipitates that occur within a stratigraphic horizon in response to variations in the concentrations of solutes. While the precipitation of the concretion is controlled by the degree of supersaturation and the diffusional gradients, the kinetics of concretion formation are not well known. Precipitation processes related to concretions can entomb potential biosignatures.

Enrichment of Organic Biomarkers

Enrichment processes include all phenomena that lead to enhanced concentrations of compounds or particles. The search for biosignatures on Mars may be limited to sites with local enrichment of biosignatures, given that analytical equipment may be hampered by detection limits. Sedimentary rocks in general often enrich biomarkers on Earth, while iron oxides and clays, wherever they are found, can incorporate organic molecules.

- *Sedimentary rocks.* Sedimentation may enhance biosignature preservation in a number of ways. Sediments can provide an environment in which biomass accumulates and is buried. When sedimentation occurs as a pelagic process, settling particles may concentrate microbes that are scavenged from the water column.[2] Sediments may also preserve morphological biosignatures: Trace fossils, wrinkle marks, stromatolites, and microbialites are identifiable sedimentary forms thought to involve the interaction between sediments and microbiota.

- *Iron oxides.* Iron oxides are common minerals formed at the surface of Earth and Mars that are likely to enrich for specific types of organic molecules.[3] Organic acids may be enriched on the surface of these particles. Furthermore, organics adsorbed to iron oxides may be stable in low-pH environments.
- *Clays.* Clays preferentially adsorb organic molecules at both their surface and within the interlayer. Absorption can occur in low- or high-pH systems.

Sites and Samples for Biosignatures of Past Life

The processes that lead to preservation of biosignatures on Earth are far from fully understood. Although researchers expect their martian counterparts to follow the same general sets of processes, the conditions on Mars that may have led to biosignature preservation are poorly constrained, and hence, the matrix of target environments is necessarily varied, including sites and samples with an uncertain potential for success.

Sites Targeted for Entombment of Biosignature Molecules

A strategy to investigate martian biosignatures may focus on sites where the protection of biomolecules from degradation is expected. Three types of systems and specific sites are discussed below:

- *Hydrothermal deposits.* Because hot springs are commonly characterized by mineral supersaturation and deposition, they would be good target sites for preservation of biosignatures. However, such hydrothermal systems have not been definitively identified on Mars via remote sensing or in situ imaging. Nonetheless, proposed sites of hydrothermal activity include areas near impact craters, slopes of volcanic structures such as Hecates Tholus and Ceraunius Tholus,[4] and locations where ice melting may be occurring or have occurred.[5,6] In addition, rift systems, such as the Cerberus Fossae, may have erupted both water and lava.[7] These locations may also be sites favorable for the process of rapid mineralization and preservation of biomolecules.
- *Evaporites.* Evaporation is known to occur on Mars, as evidenced by the sulfate-rich deposits analyzed by the rover *Opportunity* in Meridiani Planum[8] and by detection from orbit of several thick deposits of sulfate minerals such as kieserite and gypsum, particularly in Valles Marineris.[9] Evaporite deposits might be likely sites for entombed organic particles.
- *Concentrations of concretions.* Concretions (termed "blueberries") are well documented at Meridiani from investigations by the rover *Opportunity*.[10] The dominant mineral of these concretions is hematite, an iron oxide that may have nucleated on organic centers and/or may have precipitated rapidly from concentrated solutions. These concretions have been concentrated as a lag deposit on the surface, where the more soluble evaporitic salts were removed by weathering processes. Sites with concretions should be considered as potential sites for biosignatures.

Sites Targeted for Enrichment of Biosignature Molecules

Sites of interest include carbon-bearing rocks and soils, layered sedimentary rocks, clays, weathered terrains, and iron oxide deposits.

- *Carbon-bearing rocks and soils.* Deposits enriched in organic carbon are prime targets for detailed analysis, either with measurements in situ or on returned samples. Organic biomarker studies on Earth typically require carbon-rich samples, and there is no reason to believe that a strategy for Mars would be different. However, to date, no carbon-rich materials have been identified on Mars.
- *Layered sedimentary rocks.* Ample evidence suggests that both surface water and groundwater existed on Mars, and that sediments accumulated from flowing surface waters and from lakes or oceans. Sedimentary rocks on Mars are found with various scales of stratification ranging from tens of meters (Figure 4.2) to very fine laminations visible in images from the rover *Opportunity*. Where deposits of sediments occurred in lakes or in a global ocean, biomolecule enrichment could have occured. Possible examples are deltas in the Holden crater.[11]

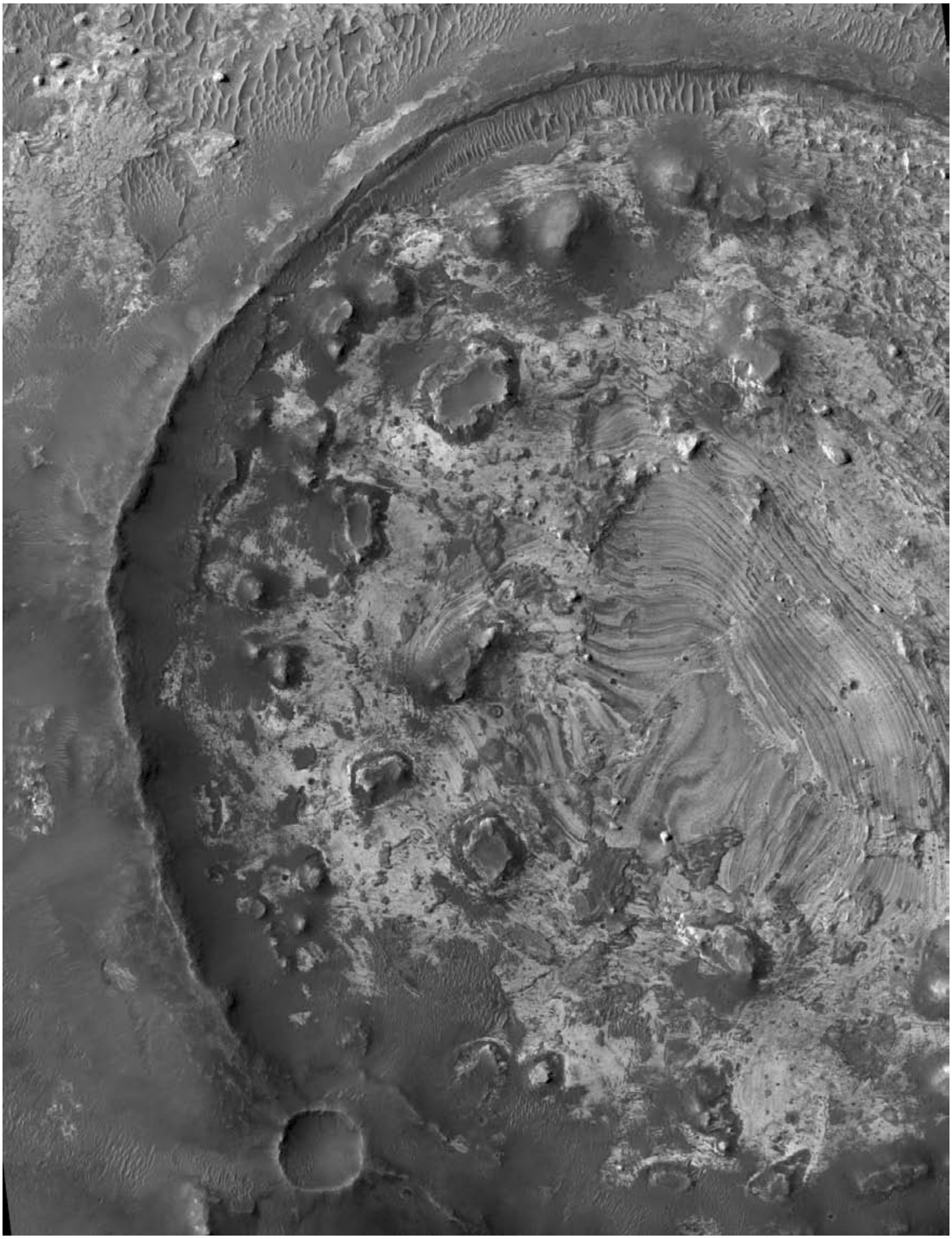


FIGURE 4.2 Layering in an unnamed crater in Meridiani Planum. The crater was once partly buried by layered deposits that have since been largely removed, leaving remnants of the former cover as mesas within the crater. The field is about 380 m across and is illuminated from the left. Image obtained by the High Resolution Imaging Science Experiment on the Mars Reconnaissance Orbiter spacecraft and provided courtesy of NASA/JPL/University of Arizona.

- *Clays.* Clays are the finest fraction in a sedimentary deposit and generally reflect deposition in waters that have minimal current or wave turbulence. The surface charge and interlayering of clay minerals enhance adsorption of organic matter; hence clays may concentrate biomolecules from the solution in which they settled. However, clays are also transported by wind and have been mixed and deposited around the planet.
- *Weathered terrains.* Bibring et al. have suggested that regions on the surface of Mars may show evidence for phyllosilicate minerals indicative of mineral weathering.[12] If these older sections of the martian crust contain clays formed at low temperature, they may be likely sites to find organic molecules remaining from cells that were living when water was present. Minerals formed during the weathering of igneous rocks are indicative of the chemistry, pH, and redox conditions of the weathering solution.
- *Iron oxides deposits.* Iron oxides are an abundant constituent of martian dust, and hematite concretions are closely associated with sulfate deposits at Meridiani. Concentrations of iron oxides, formed by geochemical processes, weathering, or Aeolian processes, could provide significant targets of astrobiological interest.

Sites Targeted for Other Biosignatures

Life harvests the available chemical energy in a rock-water-gas system or the light energy from the Sun at the same time that it extracts nutrients from the environment. A strategy for detection of extant or past life on Mars might therefore target sites where chemical energy is or was available, or sites showing evidence that nutrient extraction has occurred. Chemical systems of interest with respect to energy and nutrient needs for life include the following:

- *Carbon redox.* A likely target for any in situ or sample-return analytical mission will be the detection and analysis of carbon in both the organic and inorganic species. Methane represents C in its most reduced form, and its presence within the martian atmosphere could be a signal of biologically mediated reactions that drive C to this redox state; methane may also be an oxidizable energy source for life on this planet. Point sources of methane should be considered as targets for future investigation.
- *Sulfur redox.* The oxidation of sulfides and the reduction of sulfates are both biologically mediated reactions on Earth. A search for juxtaposed mineralogies containing the reduced and oxidized forms of S and Fe could occur at a variety of martian sites, including putative hydrothermal weathered deposits. Boundary effects may be particularly important. That is, interfaces between different minerals or fluids that are not in equilibrium may be appealing biological niches. An example of a potential target of interest is Noachian rock that may have weathered under less oxidizing conditions than immediately adjacent younger deposits.
- *Iron redox.* The abundance of iron minerals on Mars, including igneous olivine, iron oxide dust, and sedimentary hematite, provide potential redox reaction sites that may support life and may leave mineralogical evidence of past life. A target for this exploration might include sites where especially high amounts of energy are available in the form of, for example, reduced iron minerals juxtaposed with likely oxidants. The rocks of the Columbia Hills, for example, have a wide range of ferrous/ferric ratios, with ferrous-rich primary minerals in intimate contact with ferric alteration products.[13]

Morphological Biosignatures

A morphological biosignature such as a stromatolite is only likely to be found at sites where water was present and where preservational mineralogy was favorable. The formation of stromatolites in shallow aqueous settings on Earth may suggest an investigation of paleo-shorelines on Mars. Lakes were likely common when the valley networks formed in the Noachian uplands,[14] and large bodies of water must have been left at the ends of the large, post-Noachian outflow channels.[15] However, the precise location of shorelines around these former bodies of water remains controversial. Other morphological biosignatures would be most likely to form in a sediment-depositing environment, such as a former lake or paleo-ocean.

Nonredox Gradients

The formation of gradients in elemental concentration due to biological exudates may be important at the meter scale in soil horizons or regolith and at the micron scale on mineral surfaces or in endolithic communities. The assimilation of trace elements at low concentrations by microorganisms or the sequestration of toxic elements into biologically mediated precipitates could also create distributions or gradients in trace elements that record the prior presence of biota in regolith or in sedimentary environments.

SITES AND SAMPLES FOR RECENT LIFE

All biochemical reactions that sustain life require water. Hence, water (and by extension ice) is the primary focal point in site selection for the search for present life. Sites where liquid water may have been present recently at the surface include numerous gullies,[16] the ends of geologically recent outflow channels,[17] and sites of recent glaciation.[18] Water is, however, not the only target in the search for present life. Gas anomalies are also of great interest. For example, metabolic end products, including methane, carbon dioxide, and hydrogen sulfide, might indicate the presence of active local microbial communities.

Sites Containing Liquid Water

On Earth, life is active in aqueous systems over broad ranges of physicochemical conditions. Therefore, the presence of liquid water is a strong signal to follow in searching for present life.

Near the Surface

To date, there is no evidence for standing water on the surface of Mars. In fact, water is unstable under present surface conditions. However, it may persist in the shallow subsurface as part of an extensive groundwater system. Target environments where subsurface water—and hence present life—may be most likely include the following:

- Sediments and sedimentary rocks where porosity and permeability are characteristic of aquifers;
- Areas below surface features related to recent aqueous processes (e.g., gullies and young outflow channels); and
- Areas with significant concentrations of minerals such as clay or evaporates that are diagnostic of low-temperature aqueous processes and that appear to be very recent.

Surface Water in the Recent Past

Recent outflow channels and recent gullies, if they formed by groundwater seepage, could have brought subsurface organisms to the surface. In this scenario, sediments and/or ice associated with gully and channel formation could harbor dormant life as spores or cells in vegetative states. On Earth, for example, spores have been shown to survive for very long periods of time.[19] Sites of particular interest are fluvial deposits, evaporites, rocks, and minerals indicative of hydrothermal systems (e.g., hematite), and permafrost.[20] Deposits at the ends of gullies, common in mid-southern latitudes, and deposits at the ends of young outflow channels, such as those in Cerberus and to the southeast of Olympus Mons, are thus possible sites to search for dormant, but extant, life.

Water Ice

Recent Earth-based studies have demonstrated that microorganisms can survive, grow, and metabolize in frozen sediments and ice cores, where pockets of liquid water are maintained.[21] This could occur if salts are concentrated in liquid water or at the grain contacts where the freezing temperature is depressed. Relevant water-ice deposits include the following:

- *Ground ice.* Ground ice appears to be ubiquitous a few centimeters below the surface at latitudes above ~50°N and S.[22] While martian permafrost temperatures are much lower than terrestrial permafrost temperatures, these ice-rich environments have some similarities to permafrost environments found on Earth that contain many metabolizing microorganisms.
- *Glacial ice.* Deposits left by cold-based glaciers have been identified on Mars, particularly on the northwest flanks of the large Tharsis volcanos.[23] They probably formed in recent geological times during periods of high obliquity and might therefore still contain dormant lifeforms or their remnants.[24]
- *Polar ice caps.* Thick (up to several km), layered sediments of dust and ice are exposed in the polar ice caps, which extend to ~80°N and S latitude (Figure 4.3). Owing to chaotic oscillations of Mars's obliquity,[25] the

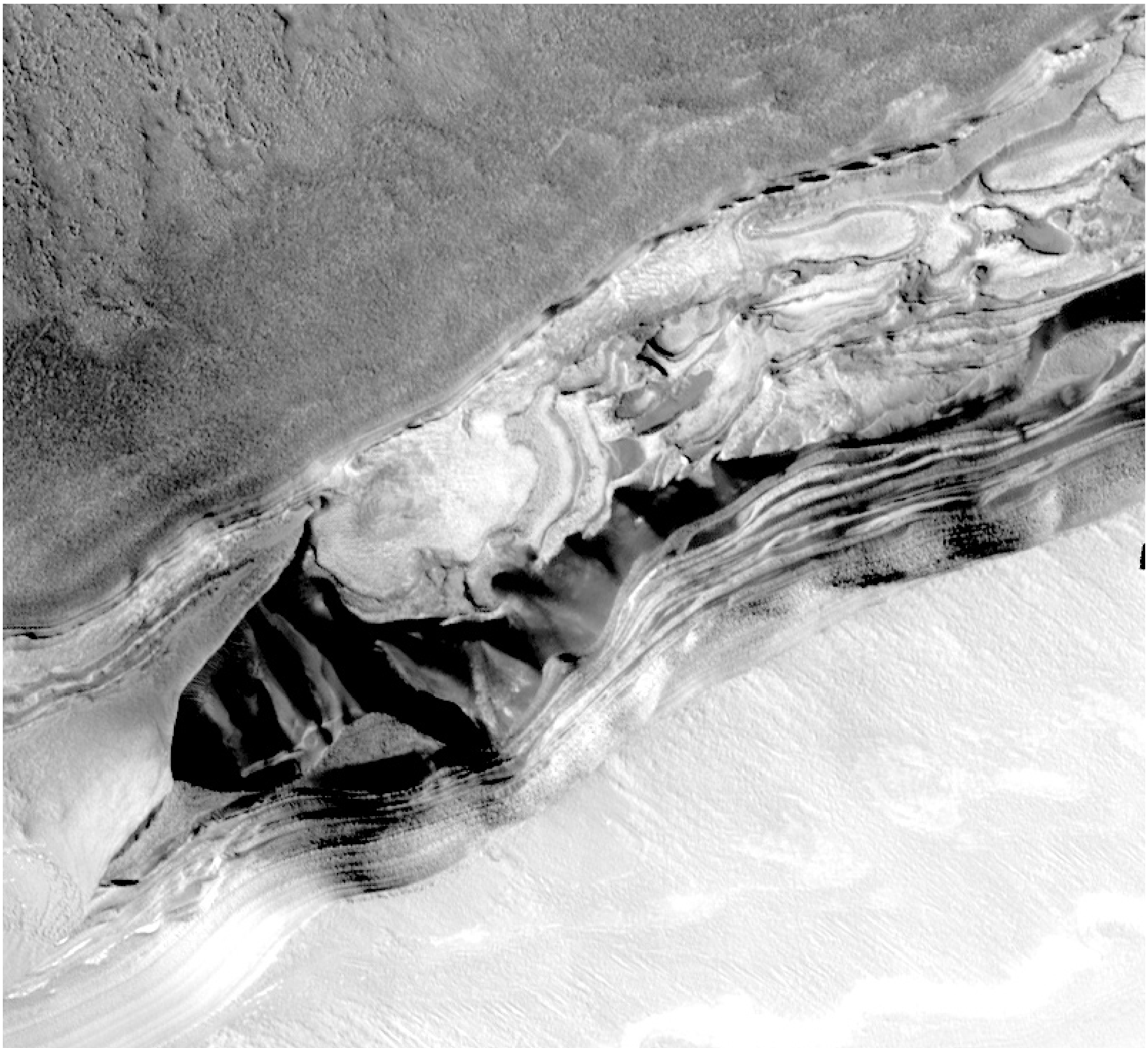


FIGURE 4.3 Layered deposits near Mars's north pole. The intricate patterns in the middle of the image are caused by gypsum-rich dunes exposed in a cliff. The smooth areas to the upper left and lower right are more typical of the deposits that surround the north pole. Image obtained by the High Resolution Imaging Science Experiment on the Mars Reconnaissance Orbiter spacecraft and provided courtesy of NASA/JPL/University of Arizona.

polar regions may experience periodic temperatures near the melting point of water ice, making the cap environments potentially habitable to extremely psychrophylic (cold-loving) microorganisms.

Localized Gas Fluxes

The metabolisms of many microorganisms create gaseous end products. These include CH_4, CO_2, H_2S, N_2, NH_3, H_2, and O_2. CH_4 is of particular interest with respect to Mars, owing to recent claims of its detection.[26–28] On Earth, most of the atmospheric methane is biogenic, produced by aceticlastic or chemolithoautotrophic archaea; a recent study also ascribes the production of methane to plants.[29] However, processes of abiogenic methane production also need to be considered. These include metamorphism/reduction of carbonates, serpentinization of olivine and subsequent abiotic reduction of CO_2 with the generated H_2, and recycling/thermal cracking of deeply buried complex organic matter (e.g., kerogen). Despite the ambiguity of methane as a biomarker,[30] sites on Mars where methane is clearly detected are high-value targets in the search for present (presumably subsurface) life.

SUMMARY

There are a wide range of sites on Mars that merit astrobiological investigation. These include sites of possibly active water at the present, sites that have had recent water and could conceivably harbor dormant organisms, and sites that had ancient water. It is difficult to prioritize these from a scientific perspective, as they each represent viable and valid regions for study, and each will contribute greatly to astrobiological understanding of Mars. In addition, the technological requirements for exploring each are not at present well defined, such that it is difficult to know which will be most fruitful for the next one to two decades. However, a general statement is that the highest priority should go to sites where liquid water is or was present and where abundant energy is available that can drive metabolism.

REFERENCES

1. B.W. Fouke, J.D. Farmer, D.J. Des Marais, L. Pratt, N.C. Sturchio, P.C. Burns, and M.K. Discipulo, "Depositional Facies and Aqueous-Solid Geochemistry of Travertine-Depositing Hot Springs (Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, U.S.A.)," *Journal of Sedimentary Research* 70:265-285, 2000.

2. L.E. Collins, W. Berelson, and D. Hammond, "Microbial Hitchhikers: The Flux of Bacteria on Particles Raining Through the Oxygen Minimum Zone, San Pedro Basin, CA," *Eos* 87(36), Ocean Sciences Meeting Supplement, Abstract OS23H-06, 2006.

3. B. Gu, J. Schmitt, Z. Chen, L. Liang, and J.F. McCarthy, "Adsorption and Desorption of Natural Organic Matter on Iron Oxide: Mechanisms and Models," *Environmental Science and Technology* 28:38-46, 1994.

4. M.H. Carr, *The Surface of Mars*, Cambridge University Press, New York, N.Y., 2006.

5. J. Farmer, "Hydrothermal Processes on Mars: An Assessment of Present Evidence," in *Evolution of Hydrothermal Ecosystems on Earth (and Mars ?)*, G. Bock and J. Goode (eds.), J. Wiley and Sons, N.Y., 1996.

6. J.A. Rathbun and S.W. Squyres, "Hydrothermal Systems Associated with Martian Impact Craters," *Icarus* 157:362-372, 2002.

7. D.M. Burr, A.S. McEwen, and S.E. Sakimoto, "Recent Aqueous Floods from the Cerberus Fossae, Mars," *Geophysical Research Letters* 29:1, doi:10.1029/2001Gl013345, 2002.

8. S.W. Squyres, R.E. Arvidson, J.F. Bell, J. Bruckner, N.A. Cabrol, W. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W. Farrand, W. Folkner, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, L. Haskin, K.E. Herkenhoff, S. Hviid, J. Johnson, G. Klingelhöfer, A.H. Knoll, G. Landis, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice, Jr., L. Richter, R. Rieder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, H. Wänke, T. Wdowiak, M. Wolff, and A. Yen, "The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars," *Science* 306:1698-1714, 2004.

9. J. Bibring, Y. Langevin, J.F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold, P. Pinet, F. Forget, and the OMEGA team M. Berthé, J. Bibring, A. Gendrin, C. Gomez, B. Gondet, D. Jouglet, F. Poulet, A. Soufflot, M. Vincendon, M. Combes, P. Drossart, T. Encrenaz, T. Fouchet, R. Merchiorri, G. Belluci, F. Altieri, V. Formisano, F. Capaccioni, P. Cer-

roni, A. Coradini, S. Fonti, O. Korablev, V. Kottsov, N. Ignatiev, V. Moroz, D. Titov, L. Zasova, D. Loiseau, N. Mangold, P. Pinet, S. Douté, B. Schmitt, C. Sotin, E. Hauber, H. Hoffmann, R. Jaumann, U. Keller, R. Arvidson, J.F. Mustard, T. Duxbury, F. Forget, and G. Neukum, "Global Mineralogical and Aqueous History Derived from OMEGA/Mars Express data," *Science* 312:400-404, 2005.

10. S.W. Squyres, R.E. Arvidson, J.F. Bell, J. Bruckner, N.A. Cabrol, W. Calvin, M.H. Carr, P.R. Christensen, B.C. Clark, L. Crumpler, D.J. Des Marais, C. d'Uston, T. Economou, J. Farmer, W. Farrand, W. Folkner, M. Golombek, S. Gorevan, J.A. Grant, R. Greeley, J. Grotzinger, L. Haskin, K.E. Herkenhoff, S. Hviid, J. Johnson, G. Klingelhöfer, A.H. Knoll, G. Landis, M. Lemmon, R. Li, M.B. Madsen, M.C. Malin, S.M. McLennan, H.Y. McSween, D.W. Ming, J. Moersch, R.V. Morris, T. Parker, J.W. Rice, Jr., L. Richter, R. Rieder, M. Sims, M. Smith, P. Smith, L.A. Soderblom, R. Sullivan, H. Wänke, T. Wdowiak, M. Wolff, and A. Yen, "The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars," *Science* 306:1698-1714, 2004.

11. M.C. Malin and K. S. Edgett, "Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars," *Science* 302:1931-1934, 2003.

12. J. Bibring, Y. Langevin, J.F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold, P. Pinet, F. Forget, and the OMEGA team M. Berthé, J. Bibring, A. Gendrin, C. Gomez, B. Gondet, D. Jouglet, F. Poulet, A. Soufflot, M. Vincendon, M. Combes, P. Drossart, T. Encrenaz, T. Fouchet, R. Merchiorri, G. Belluci, F. Altieri, V. Formisano, F. Capaccioni, P. Cerroni, A. Coradini, S. Fonti, O. Korablev, V. Kottsov, N. Ignatiev, V. Moroz, D. Titov, L. Zasova, D. Loiseau, N. Mangold, P. Pinet, S. Douté, B. Schmitt, C. Sotin, E. Hauber, H. Hoffmann, R. Jaumann, U. Keller, R. Arvidson, J.F. Mustard, T. Duxbury, F. Forget, and G. Neukum, "Global Mineralogical and Aqueous History Derived from OMEGA/Mars Express Data," *Science* 312:400-404, 2006.

13. S.W. Squyres, R.E. Arvidon, D.W. Blaney, B.C. Clark, L. Crumpler, W.H. Farrand, S. Gorevan, K.E. Herkenhoff, J. Hurowitz, A. Kusack, H.Y. McSween, D.W. Ming, R.V. Morris, S.W. Ruff, A. Wang, and A. Yen, "The Rocks of the Columbia Hills," *Journal of Geophysical Research* 111:E02S11, doi:10.1029/2005JR002562, 2006.

14. N.A. Cabrol and E.A. Grin, "Distribution, Classification and Ages of Martian Impact Crater Lakes," *Icarus* 142:160-172, 1999.

15. S.M. Clifford and T.J. Parker, "The Evolution of the Martian Hydrosphere: Implications for the Fate of a Primordial Ocean and the Current State of the Northern Plains," *Icarus* 154:40-79, 2001.

16. M.C. Malin and K.S. Edgett, "Evidence for Recent Groundwater Seepage and Surface Runoff on Mars," *Science* 288:2330-2335, 2000.

17. J.W. Head, L. Wilson and K.L. Mitchel, "Generation of Recent Water Floods at Cerberus Fossae, Mars by Dike Emplacement, Cryosphere Cracking and Confined Aquifer Groundwater Release," *Geophysical Research Letters* 30(11):1577, doi:10.1029/2003GL017135, 2003.

18. J.W. Head, D.R. Marchant, M.C. Agnew, C.I. Fassett, and M.A. Kreslavsky, "Extensive Valley Glacier Deposits in the Northern Mid-Latitudes of Mars: Evidence for Late Amazonian Obliquity-Driven Climate Change," *Earth and Planetary Science Letters* 241:663-671, 2005.

19. See, for example, W.L. Nicholson, N. Munakata, G. Horneck, H.J. Melosh, and P. Setlow, "Resistance of Bacillus Endospores to Extreme Terrestrial and Extraterrestrial Environments," *Microbiology and Molecular Biology Reviews* 64(3):548-572, 2000; and references therein.

20. M.R. Walter and D.J. DesMarais, "Preservation of Biological Information in Thermal Spring Deposits: Developing a Strategy for the Search for Fossil Life on Mars," *Icarus* 101:129-143, 1993.

21. See, for example, J.C. Priscu and C. Christner, "Earth's Icy Biosphere," pp. 130-145 in *Microbial Diversity and Prospecting*, A.T. Bull, ed., ASM Press, Washington, D.C., 2004.

22. W.C. Feldman, T.H. Prettyman, S. Maurice, J.L. Plaut, D.L. Bish, D.T. Vaniman, M.T. Mellon, A.E. Metzger, S.W. Squyres, S. Karunatillake, W.V. Boynton, R.C. Elphic, H.O. Funsten, D.J. Lawrence, and R.L. Tokar, "The Global Distribution of Near Surface Hydrogen on Mars," *Journal of Geophysical Research* 109(E9):E09006, doi:10.1029/2003JE02160, 2004.

23. J.W. Head and D.R. Marchant, "Cold Based Mountain Glaciers on Mars: Western Arsia Mons," *Geology* 31:641-644, 2003.

24. B.M. Jakosky, R.M. Haberle, and R.E. Arvidson, "The Changing Picture of Volatiles and Climate on Mars," *Science* 310:1439-1440, 2005.

25. J. Laskar, B. Levrard, and J.F. Mustard, "Orbital Forcing of the Martian Polar Layered Deposits," *Nature* 419:375-377, 2002.

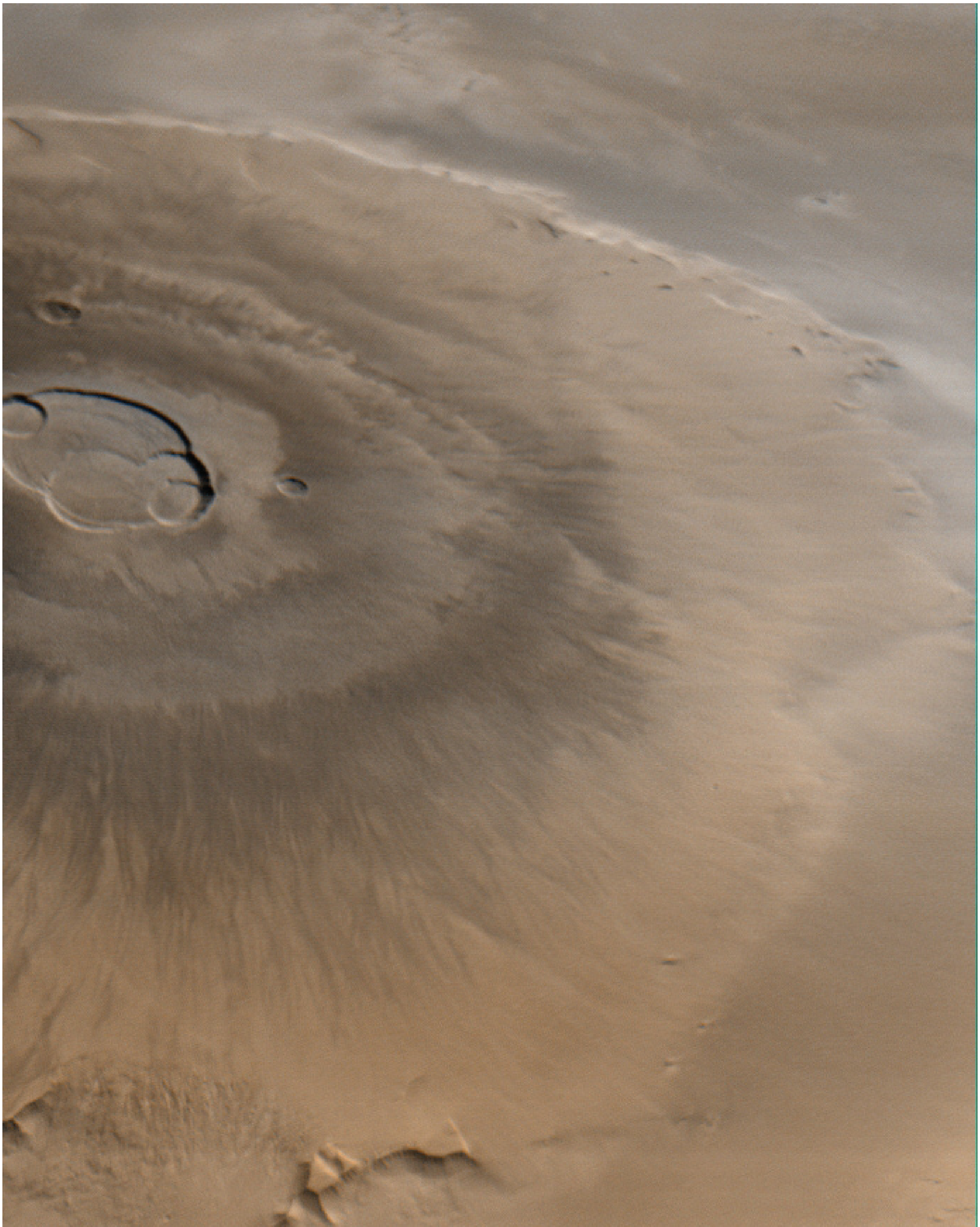
26. V. Formisano, S. Atreva, T. Encrenaz, N. Ignatiev, and M. Giuranna, "Detection of Methane in the Atmosphere of Mars," *Science* 306:1758-1761, 2004.

27. V.A. Krasnopolsky, J.P. Maillard, and T.C. Owen, “Detection of Methane in the Martian Atmosphere: Evidence for Life?,” *Icarus* 172:537-547, 2004.

28. M.J. Mumma R.E. Novak, M.A. DiSanti, B.P. Bonev, and N. Dello Russo, “Detection and Mapping of Methane and Water on Mars,” *Bulletin of the American Astronomical Society* 36:1127, 2004.

29. F. Keppler, J.T.G. Hamilton, M. Brass, and T. Roeckmann, “Methane Emissions from Terrestrial Planets under Aerobic Conditions,” *Nature* 439:187-191, 2006.

30. M. Allen, B. Sherwood Lollar, B. Runnegar, D.Z. Oehler, J.R. Lyons, C.E. Manning, and M.E. Summers, “Is Mars Alive?,” *Eos* 87:433-439, 2006.



5

Methodologies for Advancing Astrobiology

ORBITAL MEASUREMENTS AT GLOBAL AND REGIONAL SCALES

Measurements at global and regional scales are a necessary and important component of a Mars astrobiology strategy. Such measurements allow global, regional, and local characterization of properties as well as the elucidation of global processes that affect habitability.

Although liquid water is not stable at the surface today, it could persist in the subsurface for extended periods of time. There, chemical reactions involving water and the surrounding regolith could provide energy that could support metabolism of organisms or, conceivably, the chemical reactions that might lead to life. Researchers are learning that Earth's subsurface biosphere may be comparable in size to that at its surface, and it is expected that any extant biosphere on Mars would involve organisms in the subsurface. Subsurface liquid water could be detected from the surface or from orbit by radar and microwave techniques, based on the distinct dielectric behavior of water compared to ice, rock, or regolith. Wavelengths can be selected that would allow sensitivity to different depths beneath the surface, allowing subsurface sounding and profiling at various length scales. The anticipated results would include the potential discovery of subsurface deposits of water and determination of its geographical distribution. The next logical step would be direct, in situ access to the subsurface via drilling.

Measurements from the Mars Exploration Rovers and from the Mars Express orbiter, combined with other evidence, increasingly point to a warmer and/or wetter ancient environment compared to the present cold and dry climate. Determining the processes by which the atmosphere evolved is central to understanding the nature of martian habitability in particular and planetary habitability in general, and provides a key boundary condition to the possible occurrence of martian life. Direct measurements from Mars Express show that atmospheric atoms and molecules are being lost to space today, and isotopic measurements indicate that this loss has been an important process through time and may have been the dominant loss mechanism. A thorough understanding of the structure, composition, and dynamics of the upper atmosphere today, and of the solar- and solar-wind-driven loss processes and how they operate today, and an understanding of how they vary with properties of the incoming solar and solar

FIGURE 5.1 Olympus Mons is the largest known volcano in the solar system, rising about three times higher than Mount Everest. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems. The image covers an area of 168 by 124 km.

wind inputs will allow a determination of how these processes operated through time and how important loss to space has been over time. These measurements will require global-scale observations that can be made through a combination of in situ and remote-sensing approaches from orbit. They would address the current inadequate information in this area today.

If Mars has active geological processes that involve gas exchange between the surface and the subsurface (such as outgassing associated with volcanism or gas exchange between the atmosphere and a deep aquifer), there should be evidence of this in atmospheric trace gases. There also is likely to be trace-gas evidence if Mars has a large, active surface or subsurface biosphere. Methane has been discussed in this context recently, due to its reported detection by three different groups. However, atmospheric methane can result from either of these sets of processes. Distinguishing between the two would require measurements of other trace gases (e.g., formaldehyde) that would be produced by only one of the processes. Thus, global-scale measurements of atmospheric gases, with sufficiently high precision and accuracy to allow detection and characterization of trace gases, would be a valuable astrobiology objective. There also is the possibility that observations can be made in a nadir-pointing mode—the preferred approach when trying to identify a localized source—that would provide high-spatial-resolution mapping of trace gases, which could in turn allow identification of a localized source of trace gases and their potential temporal variability.

Other regional- and global-scale measurements would contribute to astrobiological science goals. These might include high-resolution spectroscopic mapping that would allow identification of mineralogy associated with water- or volcanic-related geological features, geophysical measurements that would determine the thermal history and subsurface structure, and mapping of polar deposits at all wavelengths that would provide information on their history and the potential occurrence of liquid water.

GEOLOGICAL AND ENVIRONMENTAL CONTEXT AT LOCAL SITES

The plausibility of life existing at a given landing site depends on the location having a habitable environment. The recognition and characterization of present environments are straightforward. If such an environment existed in the past, then the geological history of that site must have allowed preservation of an environmental record and of traces of organisms that populated it. Past environments and historical geology can be retrieved from rocks using in situ instruments, as demonstrated by rovers such as Mars Pathfinder's *Sojourner* and the Mars Exploration Rovers, *Spirit* and *Opportunity*.[1,2] These missions clearly demonstrate that the keys to unraveling geological and environmental context are mobility and a complementary suite of instruments for observations and measurements.

The geologically active surface of Earth constitutes a major hurdle for recognizing the remains of its ancient life. Surface rocks on Mars, as far as we know, have not experienced the thermal (metamorphic) and deformational (tectonic) events that so commonly obscure the record of life in terrestrial Precambrian rocks. However, several processes can potentially complicate astrobiological studies of Mars rocks:

- *Volcanism.* Much of the planet's surface is covered with lava flows that would destroy any surface or near-surface organisms. The limited number of impact craters on some terrains and the young ages of many martian meteorites indicate that volcanic activity has continued throughout Mars's history. Understanding the timing of volcanism at a local site, relative to the age of any putative life forms, is critical to any hypothesis for martian life.
- *Shock metamorphism.* Meteor impacts transmit large shock pressures to target rocks, transforming minerals, pulverizing rocks, and sometimes melting them. Shock metamorphism is pervasive in martian meteorites, and the high density of craters in ancient Noachian terrains (arguably the most intriguing sites for life) argues that most of these rocks have experienced shock. Cratering also excavates materials, thus disrupting the outcrop stratigraphy that is so useful in reconstructing geological history and environments.
- *Weathering.* The spectral identification of readily weathered igneous minerals (olivine and pyroxene) at regional and local scales suggests that weathering processes on Mars might be dominated by physical rather than chemical weathering. However, alteration processes in soils and alteration rinds on rocks reveal chemical dissolution reactions that could potentially obscure evidence for life.[3] In that case, mechanisms for accessing fresh rock

interiors (MER rovers utilized a rock abrasion tool) are required. It is also possible that weathering could produce chemical gradients at rock surfaces that might actually be exploited by microorganisms, and so examination before and after grinding or drilling may be desirable.

Global-scale observations by orbiting spacecraft also have a role in the geological exploration of local sites. As an example, orbital imagery of channels was instrumental in interpretations of the geological history of the Mars Pathfinder landing site. As another, chemical biomarkers must be detected in the context of the global environment. The ^{13}C biomarker is a good indicator of life, but only if nonbiological fractionations in ^{13}C in the carbon dioxide background are known (see Chapter 3).

Determining the geological and environmental history of a local site provides a critical filter for assessing the plausibility of life at that site. Remote sensing by instruments on rovers and orbiters can provide adequate characterization in most cases, although advances in the identification of minerals and measurement of trace elements and isotopes (which constrain environments) and in geochronology (which constrains geological history) are needed.

IN SITU ANALYSES RELATED TO LIFE DETECTION

Measurements Required

From the lessons learned from ALH 84001 and the early life on Earth debate (see Chapter 2), a multi-instrument, multi-measurement strategy must be used in robotic exploration and analyses to be able to make statements about the presence of biomarkers with any confidence. Although the focus of this section is in situ measurements, the same capabilities apply to the collection and analysis of samples returned from Mars. In situ astrobiological instruments must provide for the following tasks:

- Acquire appropriate samples,
- Understand the context,
- Identify the best place on the sample for further analysis, and
- Perform a number of mutually confirming independent measurements.

Accomplishing these tasks requires that any mission be able to identify suitable samples from a distance; perform contact instrument analysis to confirm suitability of the sample for further investigation (sometimes called sample triage); and utilize a suite of instruments to analyze a selected portion of the sample, either in situ on Mars or in terrestrial laboratories on returned samples. These instruments should be capable of making the following observations and measurements:

- *Comprehensive imaging.* Image each investigation scene to assess the variety of local environments expressed in surface features such as outcrops.
- *Definitive mineralogy and chemistry.* Determine mineralogical and chemical (elemental) composition at all scales of investigation: site/scene surface reconnaissance scale (range: infinity/horizon to meter; resolution: kilometer to centimeter); hand-sample scale (range: meter to centimeter; resolution: centimeter to millimeter); and acquired subsample scale (bulk measurement of a few grams or milligrams of subsample with high accuracy).
- *Redox potential.* Assess the redox potential and oxidation chemistry of materials in the near-surface environment.
- *Fine-scale surface analyses.* Investigate the surfaces of selected exposed or acquired samples at fine scales for morphological, chemical, and molecular signatures suggesting preservation of prebiotic or biotic organic compounds. This may include directly detected compositional markers, evidence of minerals formed in or altered by liquid water, or particular sample textures. Color optical (microscopic) imaging with a high resolution should also be used to provide context for any co-focused spectroscopic tools such as ultraviolet-excitation fluorescence, laser Raman, or other fine-scale techniques to perform chemical signature detection.

- *Subsample biosignature analyses.* On selected subsamples, perform an array of high-sensitivity, mutually confirming laboratory investigations as described below.

Biosignatures

The identity, abundance, and isomeric distribution of carbon compounds should be analyzed to low detection levels (parts per billion or below by weight within bulk ~100-mg subsamples) and to high molecular weights (hundreds to thousands of Daltons) at high peak resolutions. Mass spectrometry measurements should be configured to enable the detection of less volatile species that are relevant to the preservation of biosignatures. The isotopic ratios of C, H, N, O, P, and S should be characterized with sufficient precision to enable biogenic, environmental, or meteoritic fractionation trends to be identified. Compound-specific isotope analyses are highly desirable. Additional isotope ratios that further characterize atmospheric components and aqueous processes are also needed.

Highly sensitive tests for the presence and characteristics of specific biosignatures should be conducted on bulk subsamples or isolated extraction products (e.g., phases or concentrates). Biosignatures of particular interest include the identities or abundances of molecular compounds of distinctly biological origin as known on Earth, indicators of extant metabolic processes such as disequilibrium chemistry, and chemical or morphological traces of such compounds and processes preserved in minerals. Examples of specific tests include detection of amino and nucleic acids, lipids, and proteins; determination of chirality in amino acids and sugars; detection of enhanced concentrations of molecules that suggest selective use of specific isomers; and observations of cellular morphology or microfossils.

In Situ Flight Instrumentation Needed

Instruments that can make the observations and measurements required for astrobiology are not generally at the technology readiness level necessary to allow their inclusion in Mars missions. New developments in instrumentation are being fueled by the medical industry and by concerns about biowarfare agent detection and should be incorporated into spacecraft mission planning. Examples of new technologies include the following:

- *Microelectromechanical systems.* This technology takes advantage of new techniques for manufacturing miniaturized components, producing smaller, sensitive instruments for portable use.
- *Microelectro-optical systems.* These optic systems would provide more capable imaging and spectroscopy.
- *Microfluidics.* Sometimes called "lab on a chip," these fluidic circuits when cut into a glass or plastic wafer can transport and mix fluids, bring dried reagents into contact with fluid to perform reactions, combine liquid with electrical currents for electrophoresis or sample concentration, and perform sensitive measurements on analytes of interest.
- *Imaging*. Atomic-force microscopy is being used on both the Rosetta and the Phoenix missions. Currently it is the only way to image in space beyond the limitations of optical devices. Other imaging technologies including interferometry, scanning near-field optical microscopy, and electron microscopy techniques should also be developed for spaceflight applications.
- *Imaging spectroscopy.* Coupling spectroscopy to imaging is an extremely powerful tool for elucidating the chemistry of any sample. An example relevant to astrobiology is the use of imaging-Raman systems detect reduced carbon in microfossils and in ALH 84001.[4-7] The use of multiple/tunable laser systems, light-emitting diodes, and advances in miniaturization and detector design have direct relevance to spacecraft spectrometers.
- *Mass spectrometry*. Mass spectrometry (MS) coupled to some form of gas chromatography (GC) system is the method of choice for unambiguous identification of organic molecules. The chromatography is essential to resolve and obtain the characteristic spectra of isobaric compounds and determine their relative abundances. Instruments used for Mars exploration would likely exploit the well-established technologies of electron impact ionization and quadrupole or time-of-flight (TOF) mass analyzers. Given the low expected abundances of organic molecules in Mars samples, attention should be paid to improving sensitivity over that of existing methodologies.
- *Biotechnology*. Key technologies for life detection involve specific recognition of a target of interest using a probe molecule. A probe molecule is one that has a site that interacts specifically with the target, allowing its con-

centration and detection by various means. Common probes are antibodies, FAb fragments, DNA/RNA aptamers, and molecular imprinted polymers or capture resins. Detection of the target molecules can occur via optical means (fluorescence or colorimetry), mass spectrometry, or surface plasmon resonance.

- *Sample-handling technology.* A major hurdle for in situ investigations of biomarkers is the availability of robust and flexible sample-handling systems. Most measurements for biosignatures require that the sample be pretreated in some fashion. The extraction of biomolecules and their introduction into instruments without cross-contamination or biasing the concentrations of molecules of interest, allowing the concentration of the sample to increase the likelihood of detection, and ensuring that no poisoning compounds or ions come into contact with the sample, is critical.

MARS METEORITE COLLECTION AND ANALYSIS

There are currently more than three-dozen examples of the so-called SNC (shergottite, nakhlite, and chassignite) meteorites believed to have originated on Mars.[8] All of these meteorites are igneous rocks whose source localities on Mars are unknown. Most of the known martian meteorites have crystallization ages younger than ~1.3 billion years.[9] Only one, the orthopyroxenite ALH 84001 with its crystallization age of ~4.5 billion years, is likely to represent a sample of the ancient crust of Mars that is most likely to have had environments that could have hosted life.[10,11]

Given the lack of geological context for the martian meteorites, their origin from a limited number of mostly young volcanic terrains on Mars, alteration by shock and cosmic irradiation during their ejection from Mars and delivery to Earth, and subsequent weathering and contamination by organisms in a terrestrial environment, the martian meteorites are not ideal for astrobiological investigations. Nevertheless, some of them contain clear evidence for low-temperature alteration by aqueous fluids, and investigations of these samples have provided significant constraints on the near-surface environment and the history of water on Mars.[12,13] Ancient ALH 84001 in particular has been the focus of numerous (often controversial) studies that may have implications for past biogenic activity on Mars.[14–17] Therefore, although not optimal, the martian meteorites still provide a relatively inexpensive means of investigating the potential for past and/or present life on Mars.

In recent years, many new members of this clan have been recovered from hot and cold desert regions of the world. Although the terrestrial residence time of martian meteorites collected in hot and cold deserts is about the same, the former are much more subject to terrestrial weathering and biological contamination than the latter.[18,19] Because those meteorites collected in Antarctica have spent most of their time on Earth fully encased in ice, they do not, in general, display the veins and cracks filled with alteration minerals commonly seen in meteorites found in hot deserts. Consequently, a concerted effort for the collection of martian meteorites in Antarctica should continue, given the potential scientific return from the recovery of new samples, particularly if they could provide a record of ancient and/or water-rich environments on Mars.

ANALYSES OF RETURNED SAMPLES AND STATEGIES FOR MAXIMIZING ASTROBIOLOGICAL POTENTIAL

In the development of a shorter-term strategy for the investigation of Mars from an astrobiological perspective, sample return must also be accorded a higher priority than indicated by current NASA planning.[20] Returned samples, which can be analyzed in Earth-based laboratories, offer significant advantages (Box 5.1) over remote analyses of samples by landers and rovers.[21] For the foreseeable future, the capabilities for remote analyses cannot hope to match those available in Earth-based laboratories in terms of sensitivity, accuracy, and precision. Moreover, given their severe mass- and power-limitations, spacecraft can only be equipped with a limited suite of analytical instruments, whereas the entire range of analytical capabilities available in Earth-based laboratories can be brought to bear on returned samples. Many analytical techniques require extensive sample preparation, which cannot be duplicated in remote spacecraft protocols. Analysis of chemical gradients in rocks requires spatial (depth) resolution that is difficult to achieve on Mars but would be relatively easy if done on Earth.

If properly stored and isolated from the terrestrial environment, returned samples can be examined by more sensitive analytical techniques and methodologies that are likely to be developed in the future. Returned samples

BOX 5.1
Pros and Cons of Sample Return and In Situ Analysis

Mars sample return and in situ analyses both have advantages and disadvantages, as summarized below. The two are actually quite complementary.

Mars Sample Return

Pros. The factors favoring sample return include the following:

- Ability to respond to discoveries or unexpected observations with new protocols and measurements;
- Ability to repeat experiments by multiple laboratories and confirm key results;
- Unlimited range of analytical techniques that can be applied;
- No additional requirement for development of analytical instrumentation;
- Much broader range of possible investigations;
- Participation of entire analytical community;
- Curation of samples for future investigations;
- Potential to propagate organisms if they are discovered;
- Strong complementarity with in situ analyses;
- Greater ease of identifying and addressing analytical artifacts; and
- Ability with limited mobility (i.e., by a static lander) to obtain a sample may be less costly.

Cons. The factors arguing against sample return include the following:

- Expense, given that many technologies are not yet developed and the necessary costs are uncertain;
- Requirement for infrastructure for containment and curation of samples on Earth;
- Examination of samples outside their natural environment;
- Planetary protection issues, such as those associated with, for example, forward contamination and biohazard certification;
- Potentially small sample sizes and numbers, obviating investigation of many different samples;
- Inherent complexity, and possible higher risk, of sample-return missions; and
- Potentially complex sample packaging for Earth return.

also offer great flexibility; in any scientific investigation it is advantageous to be able to alter the analytical strategy as new information emerges. This is particularly critical in astrobiological investigations, where the characteristics of extraterrestrial organisms or prebiotic chemistry cannot be confidently predicted. Some analytical flexibility has been demonstrated in Mars Exploration Rover (MER) missions, in which adaptations of instrument protocols have been employed to analyze unexpected rock compositions, but changes in sample-handling capabilities and instrumentation are clearly impossible for investigations involving remote analysis by spacecraft.

Finally, sample return is particularly important for astrobiology investigations on Mars, since it is certain that any significant finding with potentially far-reaching implications will require corroboration by multiple replications of the same analyses (ideally in different laboratories and by different investigators) and by different types of analyses. Moreover, investigations with an astrobiological focus are likely to be a significant component of any future human exploration of Mars. In addition to being of the highest scientific priority in its own right, sample return by a robotic spacecraft has been identified in several NRC reports as being an important if not essential

In Situ Analysis

Pros. The advantages of in situ analyses on Mars include the following:

- Feasibility of analysis on shorter timescale because of funding levels; more missions can be flown to multiple sites;
- Possibility of time-resolved measurements of variable processes;
- Possibility for analysis of more samples, which would provide additional context and flexibility;
- Ability to look at labile components, with no storage issues;
- Opportunity for active experimentation (manipulation of materials and observation of response);
- No planetary-protection issues associated with Earth return; and
- In situ instrument development that feeds forward for other future missions.

Cons. The disadvantages of in situ studies of martian samples include the following:

- Requirement for additional instrument and spacecraft technology development;
- Possibility that sample handling may be too complex for the types of analyses desired;
- Inability to adjust analytical capabilities in response to discoveries;
- Long lead times for instrument development;
- Inability of mission to carry more than a limited number of instruments; and
- Likelihood that some desirable analyses will never be possible in situ on Mars.

Value of Complementary Approach

In situ measurements conducted in the context of a sample-return mission have the following desirable characteristics:

- Selection of the most valuable return samples;
- Understanding of the detailed geological context in which the samples are found; and
- Potential to maximize the scientific return from the chosen samples.

precursor to any human exploration of Mars.[22–24] As such, it must be integrated into the long-term strategic planning for Mars exploration.

Various methods have been proposed to acquire martian samples. These include grab sampling (using a scoop or arm on a lander or collection of airborne dust during a flyby through the upper atmosphere), sampling a variety of rocks and soils by using a rover, obtaining subsurface samples using a drill, conducting a Phobos sample return that might contain Mars ejecta from large impacts, or collection by astronauts.

To maximize the astrobiological potential of a sample return from Mars, it will be important to recover a wide range of materials from a well-characterized site of astrobiological interest. This requirement immediately raises a longstanding strategic question: Is it appropriate to wait until sufficient knowledge has accumulated to identify the "right sample" or to get a sample from the best place identifiable today? Proponents of the "right sample" approach typically argue that spending billions of dollars to return the "wrong sample" would be a major setback to the Mars Exploration Program. The biggest concern about getting the "right sample" is that, once this approach has been accepted, the only viable sample is one for which there already is compelling evidence for life or at least a high probability of there having been life. This would seem to require obtaining a sample from a place at which detailed in situ astrobiological analysis has already been done.

That approach also presupposes that the only astrobiological value in returning a sample is determining whether life is or has been present. As already pointed out in this report, the astrobiology science goals for Mars are much broader than this, and researchers can make major progress in understanding the history of Mars, its volatiles and climate, and its geological and geophysical history by returning samples.

Related to the question of the right sample is the number of sample-return missions likely required to achieve the identified scientific goals. While some groups have attempted to estimate appropriate values for this number,[25] programmatic and fiscal realities are likely to dominate purely scientific considerations. Returning samples from Mars will cost many billions of dollars, and the history of NASA's space science activities clearly demonstrates that each major scientific community gets only one multibillion-dollar mission per decade. Thus, the only realistic number of sample-return missions that can be contemplated within the predictable time horizon is one.

Finally, reasoned and thoughtful determinations can be made today concerning where to obtain samples that would have good chances of providing valuable information on whether life is or has been present. These include likely sites of longstanding liquid water and of the geochemical potential for life. While additional data always will provide better information, sufficient data already exist to choose important sites.

The combination of the high astrobiology science value in returning samples, the seemingly impossible task of defining a single "right sample," the likely number of sample-return missions, and the ability to choose sites today that have a high potential for providing details about life suggests that the appropriate strategy is to return samples at the earliest possibility rather than continuing to wait for more data.

The selection of promising landing sites using orbital data is not infallible, and in all likelihood surprises will be encountered at every landing site. The MERs have demonstrated the ability to traverse significant distances and to analyze the diverse materials encountered on the surface and in the subsurface (exposed in craters). That demonstrated ability suggests a plausible strategy for collecting samples to be returned to Earth: Utilize all the highly mobile, well-instrumented rovers (and possibly stationary landers) in the NASA Mars exploration strategy to cache collections of interesting samples for possible future sample-return missions. A subsequent sample-return mission could then land near (possibly guided by a beacon on the cache) and retrieve a sample cache, perhaps using a tethered rover (minimizing mobility, communication, and navigation requirements) and eliminating the need for analytical instruments to assess the nature of the samples. The storage of samples should involve very simple mechanisms. Such a strategy would increase the likelihood that astrobiologically interesting samples could be obtained, and it obviously would decrease the cost of a sample-return mission (or multiple missions) significantly.

Planning for the 2009 Mars Science Laboratory is too far advanced to allow adding even a simple sample-caching capability, but this strategy should be considered for any subsequent rover (or lander, if it is to acquire subsurface samples). It may also be desirable to coordinate with the European Space Agency (ESA), to see if this strategy could be adopted for other (non-NASA) Mars rovers and landers.

While sample caching can help facilitate a Mars sample-return mission, this strategy may, according to some observers, raise issues relating to the implementation of current planetary protection policies. These concerns can be divided into those associated with forward contamination and those associated with back contamination. The former concerns arise in particular because of the potential for contaminating the martian materials collected with organisms that hitchhiked from Earth in the sample-acquisition and sample-handling systems or the caching container.[26] The latter concerns are associated with ensuring that the caching container, the samples within it, and any other spacecraft subsystems exposed to the martian environment and scheduled for return are completely sealed within the Earth-return canister prior to ascent from the surface of Mars.[27]

None of these concerns is unique to a sample-caching strategy. Indeed, all Mars sample-return scenarios must contend with all of the above planetary protection issues. Caching causes complications because some of the procedures that would only have to be implemented on a sample-return mission must now be implemented on the preceding missions that are caching samples for later return to Earth. Of particular concern is the need to ensure that the sample acquisition and handling systems undergo appropriate bioload-reduction prior to launch. If this is not done then martian materials might be contaminated with organisms from Earth as they are collected and might later cause false-positives during subsequent biological examination in a terrestrial laboratory. Yet the necessary bioload-reduction procedures are likely to be similar to those that would be required if the same sample acquisition and handling system was processing materials for an in situ detection experiment.

NASA's 1995 report *An Exobiological Strategy for Mars Exploration* advocated sample return only after Mars had been thoroughly studied at global and regional scales, and following detailed local investigations that would ensure that any returned samples would have astrobiological relevance. NASA has implemented those recommendations in its exploration planning, with the unfortunate result that Mars sample return has been repeatedly pushed to (or beyond) the end of any planning cycle. The committee suggests that the strategy advocated by the 1995 report should not delay sample caching at multiple sites; NASA should cache samples at every opportunity, and return the most interesting collection as expeditiously as possible. The scientific advantages for astrobiology of a diverse collection of rocks and soils returned to Earth from any promising site outweigh the promise of just the "right" sample at some time in the indefinite future.

This is not to say that continued characterization of the global environment and of regional and local environments is not critical to the selection of astrobiologically relevant sites. An understanding of the regional geological context of the samples at any particular site is essential for interpreting their formation histories and thus the martian paleoenvironments represented by these samples. The synergy resulting from ground-based observations and measurements, coupled with orbital data (sometimes obtained synchronously), has proven critical in investigations by the twin rovers of the MER mission at Meridiani Planum and the Gusev crater. The current suite of orbiting spacecraft at Mars (NASA's Mars Odyssey and Mars Reconnaissance Orbiter and ESA's Mars Express) have already provided and will continue to supply global and regional mapping data for Mars at unprecedented resolution. As is evident from the ongoing site selection process for the 2009 Mars Science Laboratory, there are numerous promising candidates for sites of astrobiological interest on Mars based on the available mapping.

STUDIES OF EARTH ANALOGS FOR ENVIRONMENTS ON MARS THAT MAY HARBOR LIFE

The search for extraterrestrial life begins here on Earth, with studies of both ancient rocks containing the earliest traces of terran life, and modern systems that serve as analogs for conditions and environments present on modern-day and ancient Mars. Studies of these Earth analog systems and also other Earth environments characterized by conditions of extreme temperature, pH, radiation, salinity, water activity, and so on, have greatly expanded the known range of environments that harbor life and the metabolic pathways and conditions under which life can thrive. Earth analog studies are primary drivers of astrobiological research and are also crucial for defining zones of habitability and targets for astrobiological exploration in extraterrestrial systems. However, it must be emphasized that terrestrial locations can only be used as analogs of various aspects of Mars, not as perfect analogs of an entire martian environment. Thus, when using a terrestrial analog, it is important to understand what might be similar and what might be different, and to ensure that the differences do not affect the analysis for which the analog is being used.

Studies of Earth analog sites should continue to be a fundamental aspect of Mars astrobiological research, because they provide several critical functions:

- Provide Mars-like environments for testing and development of instrumentation (e.g., via investigations supported by NASA's Astrobiology Science and Technology for Exploring Planets and Astrobiology Science and Technology Instrument Development programs) to be used on missions and a testbed for crucial real-time problem solving during missions (e.g., recent MER mobility issues).
- Allow testing of sample-collection and sample-handling protocols under Mars-like conditions, an often overlooked but critical aspect of Mars astrobiology exploration.
- Provide environments for development and validation of biosignature techniques, including establishing baseline abiotic signatures and assessment of biomarker preservation potential and alteration.
- Allow discovery of novel organisms and metabolisms and the chemical/isotopic imprints of these metabolisms on Mars-like environments. Recently identified metabolisms—not all necessarily from Earth analog sites—include nitrate-Fe respiration, H_2O radiolysis, and ammoxidation-PO_3^- respiration.

Extant life at or near Mars's surface would have to be able to endure present-day conditions of low temperature, low water activity, and intense radiation, as well as a lack of organic matter (unless methane is a factor). Such organisms may manifest only briefly, seasonally and in restricted zones where liquid water exists. Subsurface environments, such as aquifers, groundwater, and the sediments discussed above, would still be characterized by low temperature.

Cold, High, and Dry Environments

Several studies have been conducted in Earth environments with conditions closest to modern-day conditions on Mars, including high-altitude regions in South America (Altiplano) and Australia (Paralana Springs) that receive intense ultraviolet radiation, the Arctic (Svalbard/Spitsbergen-Arctic Mars), Antarctica's Dry Valleys, the Atacama Desert, basaltic rocks in the cold, dry deserts of Idaho and Oregon, and geological terrains that contain Earth's oldest rocks and earliest traces of life. The types of microorganisms associated with these environments span a range of phylogenies but are largely characterized by their ability to survive desiccation and, for those exposed at the surface, ultraviolet radiation. Organisms related to *Deinococcus radiodurans* are one example of the type of organism commonly found in many of these types of habitats.[28] The ability to withstand the damaging affects of drying and radiation, often leading to similar types of cellular damage, is a common trait. In addition to yielding information on the occurrence and survival of extremophilic microorganisms, these environments have also been used to test various analytical and sample-handling instruments proposed for in situ applications on Mars. Continued studies in Mars surface analog environments are critical for new discovery and for testing biosignature techniques and biosignature preservation.

Subsurface Refugia

As noted above, the extreme oxidizing conditions and high radiation flux at the surface of Mars provide conditions that are generally not conducive to extant life or the preservation of biomarkers. Under this premise, subsurface habitats may be the most likely refuge for life on Mars and may also provide conditions favorable for the preservation of biomarkers.

Crystalline Rocks

Some of the more intriguing analogs are deep crystalline rocks where the presence of autotrophic microbial populations is supported solely by H_2 generated via abiotic reactions such as weathering of Fe(II)-bearing silicates. The concept of a subsurface lithoautotrophic microbial ecosystem, or "SLiME," was first described for the deep basalt aquifers within the Columbia River Basalt (CRB) of south-central Washington state. The CRB microbial communities were described by Stevens and McKinley as the first discovered that are completely independent of solar-derived energy.[29] The importance of the result was not that this particular microbial ecosystem was independent of the Sun. Rather, it was the fact that communities can, in principle, exist independently of photosynthesis.

Indeed, the Stevens and McKinney results were subsequently challenged by Anderson and colleagues.[30] However, the original results are now supported by more recent results reported by Chapelle and co-workers following studies at another site.[31] The microbial communities associated with the CRB are numerically dominated by autotrophic microorganisms, bacteria capable of growth by oxidizing H_2 and fixing CO_2, including high populations of acetogens.[32] Subsequent cultivation-independent molecular analysis revealed that Archaea also accounted for 1 to 2 percent of the population of the CRB.[33] Due to the common occurrence of similar rocks on Mars—identified by their spectroscopic and morphological characteristics—and the likelihood of liquid water in the subsurface, SLiME is an attractive analog in the search for microbial life on Mars. This same basic concept has been extended from the CRB to hydrothermal waters circulating through igneous rocks in southern Idaho and to the deep groundwater of the Fennoscandian Shield. Radiolysis of water has been implicated in the millimolar concentrations of H_2 observed in the groundwater of several Precambrian Shields. These concentrations are well above those required to support H_2-utilizing microorganisms. More recently, geochemical, microbiological, and molecular analyses of alkaline saline groundwater at 2.8 kilometers depth in Archaean metabasalt in South Africa revealed a microbial community dominated by a single phylotype of sulfate-reducing bacteria (SRB) belonging to *Firmicutes*.[34] These SRB were reported to be sustained by geologically produced sulfate and H_2 at concentrations sufficient to maintain activities for millions of years. The discovery of hyperthermophilic autotrophic methanogens in conjunction with H_2 at millimolar concentrations beneath an active deep-sea hydrothermal field in the Central Indian Ocean Ridge further extended the SLiME concept to hyperthermophilic marine systems.

Deeply Buried Sediments

For reasons presented above, the subsurface is the most likely environment to harbor extant life and preserved tracers of life (biomarkers) on Mars today. Deeply buried sediments such as those beneath the seafloor on Earth are another important subsurface analog system that has yielded a wealth of new information on lithologic controls on microbial activity, especially at very low organic carbon concentrations, and on the ability of microbes to persist under extremely low nutrient conditions, leading to the requirement for refined definitions of life and death for very-slow-growing microorganisms. Parkes and colleagues have established that there is a diverse and active microbial community in deeply buried marine sediments[35] and that these organisms can persist for extended periods in spite of a relative lack of circulating fluids. Although relatively little is known about the phylogeny of these organisms, molecular analyses of deeply (~ 200 m) buried sediments from the Peru Margin indicate that the communities were dominated by bacteria in the gamma-Proteobacteria, Chloroflexi (green nonsulfur bacteria), and Archaea in the Miscellaneous Crenarchaeotic Group and South African Gold Mine Euryarchaeotic Group, and that the community composition changed with depth.[36]

Hydrothermal Systems

Direct in situ evidence for hydrothermal activity on Mars is forthcoming; however, chemical studies of SNC meteorites suggest some history of aqueous or hydrothermal alteration in Mars's past, and current juxtaposition of water-rich and volcanic systems combined with geomorphological evidence points strongly to the existence of hydrothermal systems on Mars today or in the past. Martian hydrothermal systems, be they cold, warm, or hot, could have created environments conducive to the development and support of life. Critical studies in hydrothermal Earth analog systems (especially the low-temperature systems found in the Arctic) include studies of the initial imprinting, preservation, and subsequent alteration of potential biosignatures; determination of fossilizable components of hydrothermal deposits that may harbor biosignatures; and characterization of biogenic patterns recorded in a suite of related chemical/isotopic measurements. Hydrothermal systems on Earth have been the sites of discovery of numerous novel extremophilic organisms as well as the most ancient organisms yet found on Earth. For example, hydrothermal systems harbor many deeply branching microorganisms such as members of the *Aquificales*[37] as well as many anaerobic thermophilic archaea of the genera *Pyrococcus*, *Archaeoglobus*, and *Methanococcus*.[38] Additionally, hydrothermal systems may also preserve prebiotic compounds and serve as sites of prebiotic chemical synthesis.

Acidic and Alkaline Aqueous Systems

Findings from Mars exploration over the past decade have yielded data to suggest the occurrence of evaporative sedimentary environments and both alkaline and acidic aqueous environments during Mars's history. Accordingly, evaporative systems hosting microbial mat communities and aqueous alkaline and acid systems—groundwater and lakes (e.g., Mono Lake and Rio Tinto), and terrestrial hot springs and marine hydrothermal systems (e.g., seafloor serpentinization at Lost City, mid-ocean ridge hydrothermal deposits and seamounts)—are currently being explored for the presence of microorganisms and biosignatures preserved within the fossilizable (mineral) portions of these systems. A molecular-based study of Mono Lake microbial communities[39] revealed that most of the 212 sequences retrieved from the samples fell into five major lineages of the domain Bacteria: alpha- and gamma-Proteobacteria

(6 and 10 percent, respectively), Cytophaga-Flexibacter-Bacteroides (19 percent), high-G+C-content gram-positive organisms (Actinobacteria; 25 percent), and low-G+C-content gram-positive organisms (Bacillus and Clostridium; 19 percent). Twelve percent were identified as chloroplasts. The remaining 9 percent represented beta- and delta-Proteobacteria, Verrucomicrobiales, and candidate divisions. In contrast to the alkaliphilic Mono Lake, the acidic Rio Tinto River is host to communities that are dominated by microeukaryotes.[40] It is very important to study the behavior of chemical and isotopic biosignatures over the full range of possible environmental conditions identified on Mars in order to best apply biosignature methods to Mars samples, both in situ and returned samples.

With each new discovery from the exploration of Mars using orbiters and surface rovers comes the possiblility for newly defined Earth analogs. Most recently, findings from the MERs and Mars Express have expanded the suite of relevant Earth analogs to include sulfate-rich evaporite sediments, acidic aqueous systems hosting key indicator minerals found on Mars (e.g., jarosite, alunite), and Noachian-like systems.

TECHNICAL DEVELOPMENTS

An obvious development that would advance Mars astrobiology is precision landing of spacecraft. Landing uncertainties have decreased considerably with each landed mission (e.g., the 80- by 12-km landing ellipses of the MERs are expected to shrink to a 20-km circle for the Mars Science Laboratory (MSL)). However, astrobiology targets, such as sites of hydrothermal or fluvial activity, are likely to be small and dispersed, and better landing precision will be required to visit such locations. Similarly, implementing a robust strategy of caching samples for potential retrieval at a later date requires the development of a capability to land a spacecraft within a kilometer or less of a given point on Mars. Landing higher-mass payloads at high surface elevations requires additional development of entry, descent, and landing technology.[41]

The development of instruments for in situ measurements to address astrobiology goals is especially critical. Individual instruments are normally developed for specific missions, and there are few, if any, appropriate instruments at sufficient readiness levels currently “on the shelf.” Advances in appropriate technologies are proceeding rapidly, but there is a significant lag time in applying these new techniques to spaceflight missions. This stems in part from the special requirements that spaceflight imposes (miniaturization, modest power requirements, thermal and shock loading), but also from NASA’s lack of funding for instrument development, especially within the Astrobiology program.

As noted in an earlier chapter, the identification of poorly crystalline minerals or amorphous phases may require more advanced analytical techniques, building on the success of the MSL-designed ChemCam. Analysis of trace elements and stable isotope ratios in minerals and extracted organic matter, which is not possible with current flight instruments, also requires new technology. Improvements in imaging technology are needed for in situ examination of morphologies at submicroscopic scales. Especially important for implementation of the Astrobiology Field Laboratory may be further advances in sampling handling and processing dealing with the extraction and analysis of organic matter, with appropriate measures taken to ensure compliance with relevant planetary protection regulations. Analyses of gradients in chemistry and oxidation states in rocks are key measurements for astrobiology, and development of in situ methods having increased spatial resolution may be required. Other examples of instruments that could be developed for astrobiology are discussed in the section “In Situ Analyses Related to Life Detection” above.

Geochronology using radiogenic isotopes is an extremely challenging task, and remote sensing measurements are unlikely to provide precise or unambiguous age determinations. Absolute age data are necessary for assessment of a site’s geological history. Crater-density data provide only relative ages, and these may not be reliable in some cases because of cycles of burial and exhumation.[42] If suitable remote-sensing or in situ techniques are not available, age determinations may require the return of samples.

Despite successes in locating global and regional subsurface hydrogen (presumably ice) using gamma-ray detection (Mars Odyssey) and potentially radar sounding (Mars Reconnaissance Orbiter), methods must be developed for local electromagnetic sounding for subsurface water at specific sites. Drilling technology or other means to access subsurface fluids and rocks may be necessary, although horizontal mobility is, perhaps, more important than vertical access.

Mars sample return requires considerable technical development, and this work cannot be postponed until a few years before launch. NASA is not currently on a path to Mars sample return, because the (admittedly daunting) technology issues have not yet been addressed. A key area that must be addressed concerns the development of the technology for entry, descent, and landing systems, both at Mars and for Earth return. Another important area is so-called go-to mobility—i.e., the ability to identify a rock and have a rover autonomously approach and collect a sample. Such a capability would provide for more efficient sampling. The MSL-designed coring device is a significant advance in sample-acquisition technology, but end-to-end sample acquisition to storage (and possibly packaging) capability must be developed. If samples are cached on the surface, as suggested above, a precision-landing capability will be needed. Retrieving cached samples, perhaps using a short-range rover with no analytical capabilities, could minimize mission complexity and cost. The development of a Mars ascent vehicle and associated mechanisms for spacecraft rendezvous, docking, and sample transfer are required if pre-collected samples are to be lofted into Mars orbit. In either case, a sample-containment mechanism that meets planetary protection requirements must be devised. Finally, Mars sample return will require that a sample-receiving facility on Earth be designed and constructed. Curated returned samples must be isolated from the terrestrial environment, not only for planetary protection, but also to preserve their scientific integrity for future studies.

REFERENCES

1. M.P. Golombek, N.T. Bridges, H.J. Moore, S.L. Murchie, J.R. Murphy, T.J. Parker, R. Rieder, T.P. Rivellini, J.T. Schofield, A. Seiff, R.B. Singer, P.H. Smith, L.A. Soderblom, D.A. Spencer, C.R. Stoker, R. Sullivan, N. Thomas, S.W. Thurman, M.G. Tomasko, R.M. Vaughn, H. Wänke, A.W. Ward, and G.R. Wilson, "Overview of the Mars Pathfinder Mission: Launch through Landing, Surface Operations, Data Sets, and Science Results," *Journal of Geophysical Research* 104(E4):8523-8554, 1999.

2. S.W. Squyres and A.H. Knoll "Sedimentary Rocks at Meridiani Planum: Origin, Diagenesis, and Implications for Life on Mars," *Earth and Planetary Science Letters* 240:1-10, 2005.

3. J.A. Hurowitz, S.M. McLennan, N.J. Tosca, R.E. Arvidson, J.R. Michalski, D.W. Ming, C. Schröder, and S.W. Squyres, "In Situ and Experimental Evidence for Acidic Weathering of Rocks and Soils on Mars," *Journal of Geophysical Research* 111:E02S19, doi:10.1029/2005JE002515, 2006.

4. J.W. Schopf, A.B. Kudryavtsev, D.G. Agresti, T.J. Wdowiak, and A.D. Czaja, "Laser Raman Imagery of Earth's Earliest Fossils," *Nature* 416:73, 2003.

5. J.M. Garcia-Ruiz, S.T. Hyde, A.M. Carnerup, A.G. Christy, M.J. Van Kranendonk, and N.J. Welham, "Self-Assembled Silica-Carbonate Structures and Detection of Ancient Microfossils," *Science* 302:1194-1197, 2003.

6. M.D. Brasier, O.R. Green, A.P. Jephcoat, A.K. Kleppe, M.J. Van Kranendonk, J.F. Lindsay, A. Steele, and N.V. Grassineau, "Questioning the Evidence for Earth's Oldest Fossils," *Nature* 416:76-81, 2002.

7. A. Steele, M. Fries, H.E.F. Amundsen, B. Mysen, M. Fogel, M. Schweizer, and N. Boctor, "A Comprehensive Imaging and Raman Spectroscopy Study of ALH 84001 and a Terrestrial Analogue from Svalbard," *Lunar and Planetary Institute* 37:2096, 2006.

8. H.Y. McSween Jr., "The Rocks of Mars, from Far and Near," *Meteoritics and Planetary Science* 37:7-25, 2002.

9. See, for example, L. Borg and M.J. Drake, "A Review of Meteorite Evidence for the Timing of Magmatism and of Surface or Near-surface Liquid Water on Mars," *Journal of Geophysical Research* 110:E12S03, doi:1029/2005JE002402, 2005.

10. See, for example, M.H. Carr, "Mars—A Water-Rich Planet?," *Icarus* 68:186-216, 1986.

11. See, for example, S.C. Solomon, O. Aharonson, J.M. Aurnou, W.B. Banerdt, M.H. Carr, A.J. Dombard, H.V. Frey, M.P. Golombek, S.A. Hauck, II, J.W. Head III, B.M. Jakosky, C.L. Johnson, P.J. McGovern, G.A. Neumann, R.J. Phillips, D.E. Smith, and M.T. Zuber, "New Perspectives on Ancient Mars," *Science* 307:1214-1220, 2005.

12. J.C. Bridges, D.C. Catling, J.M. Saxton, T.D. Swindle, I.C. Lyon, and M.M. Grady, "Alteration Assemblages in Martian Meteorites: Implications for Near-Surface Processes," *Space Science Review* 96:365-392, 2001.

13. L.E. Borg and M.J. Drake, "A Review of Meteorite Evidence for the Timing of Magmatism and of Surface or Near-Surface Liquid Water on Mars," *Journal of Geophysical Research* 110:doi:10.1029/2005JE002402, 2005.

14. See, for example, D.S. McKay, E.K. Gibson Jr., K.L. Thomas-Keprt, H. Vali, C.S. Romanek, S.J. Clemett, X.D.F. Chillier, C.R. Maechling, and R.N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH 84001," *Science* 273:924-930, 1996.

15. L. Becker, L.B. Popp. T. Rust and J.L. Bada, "The Origin of Organic Matter in the Martian Meteorite ALH 84001," *Earth and Planetary Science Letters* 167:71-79, 1999.

16. A. Steele, D.T. Goddard, D. Stapleton, J.K.W. Toporski, V. Peters, V. Bassinger, G. Sharples, D.D. Wynn-Williams, and D.S. McKay, "Investigations into an Unknown Organism on the Martian Meteorite Allan Hills 84001," *Meteoritics and Planetary Science* 35:273, 2000.

17. B.P. Weiss, S.S. Kim, J.L. Kirschvink, R.E. Kopp, M. Sankaran, A. Kobayashi, and A. Komeili, "Magnetic Tests for Magnetosome Chains in Martian Meteorite ALH 84001," *Proceedings of the National Academy of Sciences* 101:8281-8284, 2004.

18. G. Crozaz, C. Floss, and M. Wadhwa, "Chemical Alteration and REE Mobilization from Hot and Cold Deserts," *Geochimica et Cosmochimica Acta* 67:4727-4741, 2003.

19. M.R. Lee and P.A. Bland, "Mechanisms of Weathering of Meteorites Recovered from Hot and Cold Deserts and the Formation of Phyllosilicates," *Geochimica et Cosmochimica Acta* 68:893-916, 2004.

20. For a summary of NASA's current thinking on the timing of a Mars sample-return mission see, for example: D.J. McCleese and the Mars Advanced Planning Group, *Robotic Mars Exploration Strategy 2007-2016*, JPL 400-1276 706, Jet Propulsion Laboratory, Pasadena, Calif., 2006; and D.W. Beaty, M.A. Meyer, and the Mars Advanced Planning Group, *2006 Update to "Robotic Mars Exploration Strategy 2007-2016*," unpublished white paper posted November 2006 by the Mars Exploration Program Analysis Group at http://mepag.jpl.nasa.gov/reports/index.html.

21. J.L. Gooding, M.H. Carr and C.P. McKay, "The Case for Planetary Sample Return Missions: 2. History of Mars," *Eos* 70:745, 754, 755, 1989.

22. National Research Council, *Scientific Prerequisites for the Human Exploration of Space*, National Academy Press, Washington, D.C., 1993, p. 11.

23. National Research Council, Scientific *Scientific Opportunities in the Human Exploration of Space*, National Academy Press, Washington, D.C., 1994, p. 13.

24. National Research Council, *Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface*, The National Academies Press, Washington, D.C., 2002.

25. See, for example, National Research Council, *Assessment of Mars Science and Mission Priorities*, The National Academies Press, Washington, D.C., 2001, pp. 101-102.

26. For additional details see, for example, National Research Council, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

27. For additional details see, for example, National Research Council, *Mars Sample Return: Issues and Recommendations*, National Academy Press, Washington, D.C., 1997.

28. See, for example, M.J. Daly, "*Deinococcus radiodurans* as an Analogue to Extremophile Organisms That May Have Survived on Mars," pp. 67-69 in National Research Council, *The Quarantine and Certification of Martian Samples*, National Academy Press, Washington, D.C., 2002.

29. T.O. Stevens and J. P. McKinley, "Lithoautotrophic Microbial Ecosystems in Deep Basalt Aquifers," *Science* 270:450-454, 1995.

30. R.T. Anderson, F.H. Chapelle, and D.R. Lovley, "Evidence Against Hydrogen-based Microbial Ecosystems in Basalt Aquifers," *Science* 281:976-977, 1998.

31. F.H. Chapelle, K. O'Neill, P.M. Bradley, B.A. Methé, S.A. Ciufo, L.L. Knobel, and D.R. Lovley, "A Hydrogen-based Subsurface Microbial Community Dominated by Methanogens," *Nature* 415:312-315, 2002.

32. T.O. Stevens, J.P. McKinley, and J.K. Fredrickson, "Bacteria Associated with Deep, Alkaline Anaerobic Groundwaters in Southeast Washington," *Microbial Ecology* 25:35-50, 1993.

33. N.K. Fry, J.K. Fredrickson, S. Fishbain, M. Wagner, and D.A. Stahl, "Population Structure of Microbial Communities Associated with Two Deep, Anaerobic, Alkaline Aquifers," *Applied and Environmental Microbiology* 63:1498-1504, 1997.

34. L.-H. Lin, P.-L. Wang, D. Rumble, J. Lippmann-Pipke, E. Boice, L.M. Pratt, B. Sherwood Lollar, E.L. Brodie, T.C. Hazen, G.L. Andersen, T.Z. DeSantis, D.P. Moser, D. Kershaw, and T.C. Onstott, "Long-Term Sustainability of a High-Energy, Low-Diversity Crustal Biome," *Science* 314, 479-482, 2006.

35. R.J. Parkes, B.A. Cragg, S.J. Bale, J.M. Getliff, K.Goodman, P.A. Rochelle, J.C. Fry, A.J. Weightman, and S.M. Harvey, "Deep Bacterial Biosphere in Pacific Ocean Sediments," *Nature* 371:410-413, 1994.

36. P. Wellsbury, I. Mather, and R.J. Parkes, "Geomicrobiology of Deep, Low Organic Carbon Sediments in the Woodlark Basin, Pacific Ocean," *FEMS Microbiology Ecology* 42:59-70, 2002.

37. A. Rusch, E. Walpersdorf, D. deBeer, S. Gurrieri, and J. P. Amend, "Microbial Communities Near the Oxic/Anoxic Interface in the Hydrothermal System of Vulcano Island, Italy," *Chemical Geology* 224:169-182, 2005.

38. H.E. Elsaied, H. Kimura, and T. Naganuma, "Composition of Archaeal, Bacterial, and Eukaryal RuBisCO Genotypes in Three Western Pacific Arc Hydrothermal Vent Systems," *Extremophiles* 11:191-202, 2007.

39. S.B. Humayoun, N. Bano, and J.T. Hollibaugh, "Depth Distribution of Microbial Diversity in Mono Lake, a Meromictic Soda Lake in California," *Applied and Environmental Microbiology* 69:1030-1042, 2003.

40. M. Gadanho and J.P. Sampaio, "Microeukaryotic Diversity in the Extreme Environments of the Iberian Pyrite Belt: A Comparison Between Universal and Fungi-specific Primer Sets, Temperature Gradient Gel Electrophoresis and Cloning," *FEMS Microbiology Ecology* 57:139-148, 2006.

41. R.D. Braun and R.M. Manning, "Mars Entry, Descent and Landing Challenges," IEEE Aerospace Conference, Big Sky Montana, March 2006.

42. M.C. Malin and K.S. Edgett, "Mars Global Surveyor Mars Orbiter Camera: Interplanetary Cruise through Primary Mission," *Journal of Geophysical Research* 106(E10):23429-23570, 2001.

6

Astrobiological Assessment of Current Mars Mission Architecture

The Mars Exploration Program mission architecture has undergone revision approximately every 2 to 3 years in response to results obtained by ongoing and new missions and to the changing funding profiles available for future missions. The current Mars architecture, undergoing final revision as a joint effort of the NASA Jet Propulsion Laboratory Mars program office and the community-based Mars Exploration Program Assessment Group (MEPAG), provides plans up through the 2016 launch opportunity. Here, the committee describes, from the perspective of achieving astrobiology goals, the ongoing missions, those in development for launch through the end of this decade, and those in the planning stages for the next decade.

ACTIVE MISSIONS

Missions that are operating at Mars and continuing to return data as of this writing include Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, and the two Mars Exploration Rovers (*Spirit* and *Opportunity*).

Mars Odyssey

The active instruments on board Odyssey are the Gamma-Ray Spectrometer (GRS), Neutron Spectrometer (NS), High-Energy Neutron Detector (HEND), and the THEMIS instrument (Thermal Emission Imaging System, which includes a mapping infrared spectrometer and a visible imaging system). Both are providing measurements of high astrobiological relevance.

The GRS is obtaining maps of elemental abundance, including mapping of Cl and S abundances that are potentially related to aqueous processes. It also maps the H abundance that relates to polar-cap and high-latitude ground ice and to chemically bound water or transient ground ice at low latitudes. Silicon abundance is of less astrobiological relevance but can be used to map the coming and going of the seasonal polar caps, which is a strong

FIGURE 6.1 This picture of Mars's northern polar cap was taken on the 10th anniversary of the Mars Global Surveyor's launch. The clouds on the left and the north polar cap on the right compose a picture strikingly similar to an aerial view of Earth. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems.

boundary constraint on the current climate. The NS and HEND are both sensitive to near-surface H and are being used to map ground ice at high latitudes and bound water or ice at lower latitudes.

THEMIS is mapping surface composition using infrared multispectral imaging. This is able to identify surface mineralogy, which provides strong constraints on geological processes and, in particular, on places where aqueous processes have been relevant. In the visible mode, it is imaging morphological features that constrain the geological history, which is relevant to volcanism and tectonism, as well as water-related processes. In both modes, it is mapping the polar caps, which again provides constraints on the present climate and on how to extrapolate it to other epochs. THEMIS also is mapping surface physical properties using temperature measurements and, with both infrared and visible imaging, is being used to help understand potential landing sites for the Phoenix and Mars Science Laboratory missions.

Mars Express

Mars Express is the European Space Agency's first Mars orbiter. Its instrument complement includes a high-resolution stereo camera, a visible/infrared mineralogical mapping spectrometer, a subsurface sounding radar altimeter, Fourier and ultraviolet/infrared spectrometers for atmospheric studies, and an energetic neutral-atoms analyzer for studying the properties of the upper atmosphere.

The mineralogical mapping spectrometer—known as its French acronym, OMEGA—is able to map surface composition using reflectance spectroscopy by identifying characteristic absorption features. In its early mission phases, it was able to identify sulfate minerals on the surface that are strong indicators of aqueous geochemical processes, especially as constrained by the in situ measurements of the rover *Opportunity*.

The instruments designed to study the upper atmosphere are able to measure ion abundance. It has thus been possible to demonstrate that the martian upper atmosphere is being lost at present, although the net loss rate and the relationship to upper-atmospheric and solar-input processes have not been measured.

The radar sounding experiment uses long-wavelength radar that can penetrate as much as kilometers below the surface. It is able to identify subsurface structure that is related to the layering in the polar caps (Figure 6.2) and in sediments associated with impact basins.

The high-resolution stereo camera can be used to map morphology that tells researchers about ongoing geological processes. Of special interest has been the recent history of aqueous processes and of volcanism.

Mars Reconnaissance Orbiter

The Mars Reconnaissance Orbiter (MRO) is just beginning its primary science mission at this writing, and only a few preliminary results have been obtained to date. The instruments on board are a high-resolution camera (HiRISE), a high-resolution imaging spectrometer (CRISM), and a shorter-wavelength radar that can provide higher-vertical-resolution information on subsurface structure and on possible subsurface liquid water. Each of these measurements will be making significant contributions to landing-site selection for Phoenix and MSL, and each provides information that is of high value to astrobiology science objectives.

Mars Exploration Rovers

The rovers, *Spirit* and *Opportunity*, have been operating for more than 3 years and have returned a tremendous wealth of science data. Both rovers carry a panoramic imaging system (Pancam), a miniature thermal-emission spectrometer (Mini-TES), a Mossbauer spectrometer, an alpha particle x-ray spectrometer (APXS), a microscopic imager, and a rock abrasion tool (RAT). This instrument package has proved capable of characterizing astrobiologically relevant materials at landing sites selected for their high potential for having had liquid water—i.e., evaporates at Meridiani Planum and aqueously altered basaltic rocks at the Gusev crater. Not only have the rovers' instruments returned a wealth of pertinent data confirming aqueous processes at both landing sites, but both spacecraft also continue to explore the surrounding terrain and are expected to remain operational for the foreseeable future.

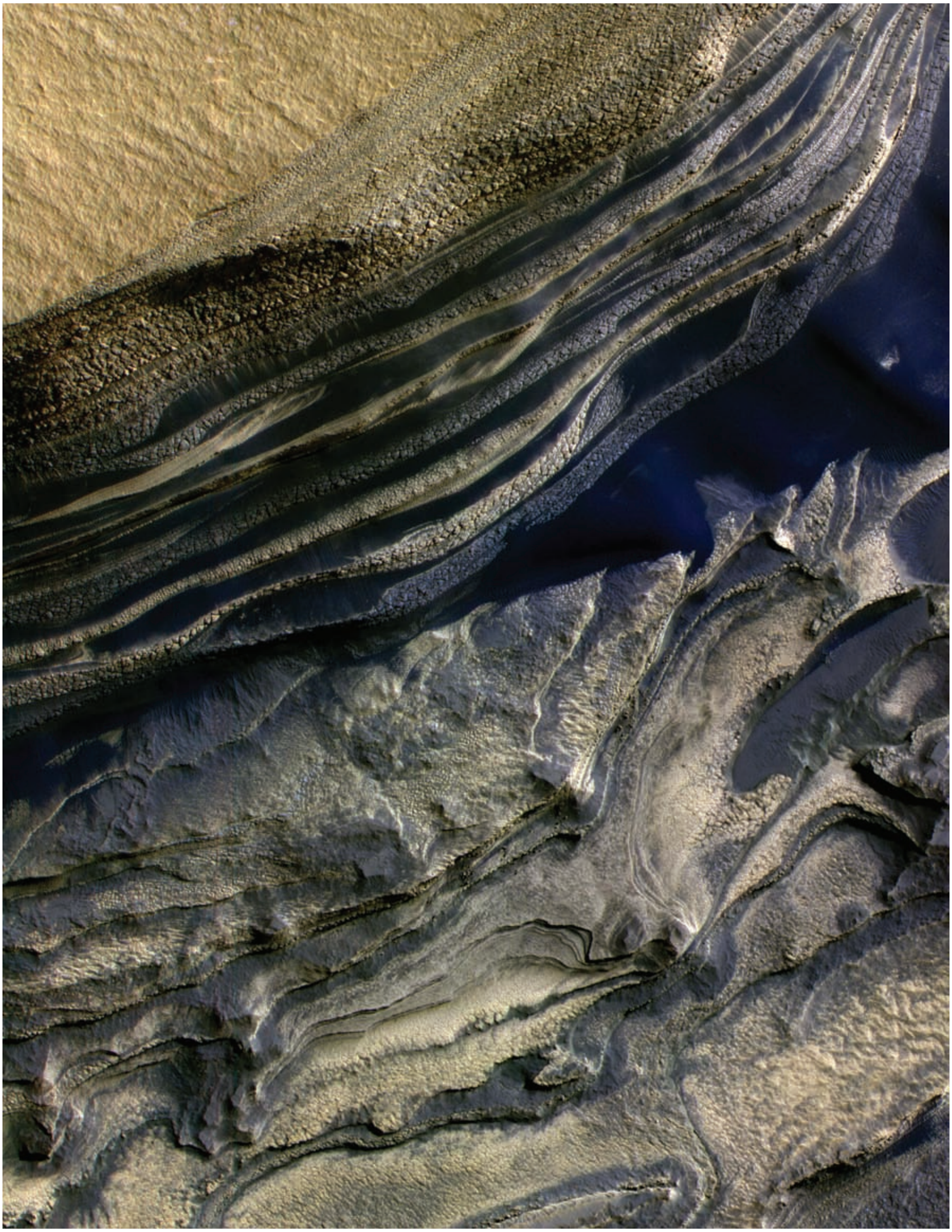


FIGURE 6.2 The intricate patterns at the bottom of this layered wall are evidence of ancient sand dunes. The dunes include gypsum, which indicates a wet past on Mars. Image obtained by the High Resolution Imaging Science Experiment on the Mars Reconnaissance Orbiter spacecraft and provided courtesy of NASA/JPL/University of Arizona.

MISSIONS IN DEVELOPMENT AND PLANNING

The Mars exploration architecture proposed by NASA envisages the launch of a mission to Mars at every possible launch opportunity, that is, every 26 months. The missions considered for the period from 2007 to 2016 are as follows:[1,2]

- 2007, Phoenix (the first competitively selected Mars Scout);
- 2009, Mars Science Laboratory;
- 2011, Mars Scout (the second competitive selection for flight);
- 2013, Mars Science and Telecommunications Orbiter; and
- 2016, Astrobiology Field Laboratory or two Mid Rovers or the Mars Long-Lived Lander Network.

Phoenix and the Mars Science Laboratory are both in phases C/D of their development. NASA selected two Mars Scout concepts for phase-A studies in early 2007. All the other missions listed above are in pre-phase-A concept-study development at the present time.

An additional mission likely to be flown in this same period is the European Space Agency's ExoMars rover, which is currently scheduled for launch during the 2013 launch opportunity.

Phoenix

The Phoenix mission, scheduled for launch in August 2007, is the first of NASA's principal-investigator-led, competitively selected Mars Scout missions. The importance of the Scout program to Mars exploration rests in its ability to address high-priority science goals related to unexpected discoveries and in the opportunity they provide for maintaining program balance. These factors led the solar and space exploration (SSE) decadal survey to rank the Mars Scout program as the highest-priority activity in the small Mars mission category.[3]

When Phoenix lands on Mars in May 2008, it will begin a program of investigations specifically designed to measure volatiles (especially water) and complex organic molecules in the arctic plains of Mars, where the Mars Odyssey orbiter has discovered evidence suggesting ice-rich soil very near the surface. The science objectives of Phoenix are as follows:

- Understand the water cycle and its interactions with the atmosphere and the regolith;
- Determine the recent history of water and its role in shaping the surface; and
- Assess whether or not the landing site is a habitable zone by looking for organics and other biogenic elements.

These objectives will be addressed via an instrument package which includes the following: a stereoscopic imager (SSI) and a descent imager (MARDI); a thermal- and evolved-gas analyzer (TEGA); a microscopy, electrochemistry, and conductivity analyzer (MECA); and a meteorological station (MET). Samples to be analyzed by TEGA and MECA will be collected with the assistance of a camera-equipped robotic arm.

Mars Science Laboratory

The Mars Science Laboratory is an advanced rover mission designed to follow the highly successful Mars Exploration Rovers, *Spirit* and *Opportunity*. The primary goal of the mission is to assess Mars's potential as a past or present abode of life, that is, to determine whether Mars ever was, or is still today, an environment able to support microbial life. The specific scientific objectives are as follows:

- Determine the nature and inventory of organic carbon compounds;
- Inventory the chemical building blocks of life (i.e., carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur);

- Identify features that may represent the effects of biological processes;
- Investigate the chemical, isotopic, and mineralogical composition of the martian surface and near-surface geological materials;
- Interpret the processes that have formed and modified rocks and regolith;
- Assess long-timescale (i.e., 4-billion-year) atmospheric evolution processes;
- Determine the present state, distribution, and cycling of water and carbon dioxide; and
- Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.

These goals will be addressed by a comprehensive suite of experiments including a panoramic mast camera (MastCam), a microscopic imager (MAHLI), and a descent imager (MARDI); an alpha particle x-ray spectrometer (APXS), a laser-induced-breakdown spectrometer and microimaging camera (ChemCam), a gas chromatograph-mass spectrometer and tunable laser spectrometer system (SAM), and an x-ray diffraction/x-ray fluorescence instrument (CheMin); an environmental radiation monitor (RAD) and a neutron spectrometer (DAN); and a meteorological package (REMS).

Although the MSL mission was not well defined at the time the SSE decadal survey was drafted, its importance to addressing key Mars science goals was recognized and this mission was determined to be the highest-priority medium-cost Mars mission for the decade 2003-2013. Since then the scope and cost of the mission have grown significantly.

The combination of MSL's highly capable science payload, its long expected lifetime, and its use of as-yet-untested entry, descent, and landing systems have led some observers to suggest that it would be prudent to send two. Indeed, NASA's 2005 *Roadmap for the Robotic and Human Exploration of Mars* recommends that two MSL spacecraft should be launched "to ensure mission success and maximize the science return."[4] Such an approach might be an appropriate risk-reduction strategy. However, its implementation at such a late stage in the development of a large and complex mission seemed ill advised, irrespective of its financial implications for the rest of the Mars program.[5]

Mars Scout 2011

NASA proposes to launch the second Mars Scout missions no later than January 2012. NASA released an announcement of opportunity for this mission in early May 2006 and, 9 months later, selected two candidates for additional studies, the Mars Atmosphere and Volatile Evolution mission (MAVEN) and The Great Escape. Given the competitive nature of the Scout program, the detailed scientific goals and capabilities of these two orbiters remain proprietary. Nevertheless, it is understood that both spacecraft are designed to address questions relating to the composition and evolution of the martian atmosphere, in general, and the structure and dynamics of the upper atmosphere and ionosphere, in particular. As such it is likely that both MAVEN and The Great Escape are responsive to the scientific goals of the Mars Upper Atmosphere Orbiter, a high-priority mission identified in the SSE decadal survey report.[6] NASA plans to select one of these two candidates for flight implementation in January 2008. In addition to selecting these two spacecraft missions, the Mars Scout program is also funding three U.S. teams providing scientific and/or instrumental contributions to the ESA's ExoMars rover mission.

Mars Science and Telecommunications Orbiter

The Mars Science and Telecommunications Orbiter (MSTO) is envisaged as being comparable in size, scope, and cost with the Mars Reconnaissance Orbiter and capable of addressing a broad range of scientific objectives associated with the study of Mars's atmosphere and space-plasma environment. Its scientific goals and instrument complement are only partially defined at the moment. Science goals endorsed in the recently completed study by MEPAG's Mars Science and Telecommunications Orbiter Science Analysis Group include the following:[7]

- Determine the interaction of the solar wind with Mars;
- Determine diurnal and seasonal variations of Mars's upper atmosphere and ionosphere;
- Determine the influence of the crustal magnetic field on ionospheric processes;
- Measure thermal and nonthermal escape rates of atmospheric constituents and estimate the evolution of the martian atmosphere;
- Measure composition and winds in the middle atmosphere; and
- Address in detail the issue of methane and other trace gases in the bulk atmosphere.

The selection in early 2007 of two Scout concept missions, both addressing the structure and dynamics of Mars's upper atmosphere, as candidates for the 2011 launch opportunity has cast some uncertainty as to the scientific scope of the mission to be flown in 2013. Since MAVEN and The Great Escape both address some of the goals listed above, the exact scientific scope of the 2013 orbiter is currently being reevaluated. Whatever the outcome of the current rescoping, this spacecraft will likely have a secondary role as a telecommunications relay to enhance the data return from surface missions such as MSL (if it is still operating) and subsequent landed missions. The dual science and mission-support role of MSTO presents issues concerning the selection of appropriate orbits. The different science goals would likely benefit from different orbits, and the telecommunications goal would require yet another orbit. Approaches could involve either compromises on the orbit or changing orbits midway through the mission.

ExoMars

ExoMars is the first flagship mission in the ESA's Aurora program of robotic and human exploration of the planets. It is a highly ambitious project involving a rover, an instrumented lander, and, possibly, an orbiting communications relay.[8] The rover was conceived as being of roughly the same size as a Mars Exploration Rover, but having the ability to carry an MSL-class payload. The science goals of ExoMars are the following:

- Search for signs of past and present life on Mars;
- Characterize the geochemistry of and distribution of water in the near-surface regolith;
- Measure the geophysical characteristics of the martian environment; and
- Identify possible surface hazards to future human missions.

These goals will be addressed by Pasteur, a comprehensive set of scientific instruments mounted on the rover, and by a separate geophysics/environmental package on the landing platform. ExoMars is currently scheduled for launch in 2013. The ambitious Pasteur package consists of remote-sensing, contact, and analytic instruments supported by a complex sample-handling system and a drill capable of extracting samples from depths of 1 to 2 meters. The latter may be particularly important if putative organic compounds, preserved in the subsurface regolith from the harsh oxidizing surface conditions, are to be studied. Instruments of particular relevance to astrobiology include a Raman/laser-induced-breakdown spectroscope, an organics and oxidants detector, a gas chromatograph-mass spectrometer, and gas and antibody-based microarray organics detectors. The results, positive or negative, from the Pasteur instruments capable of detecting organic molecules at very high sensitivity (parts per billion and better) may be key to future astrobiological studies of Mars. Overall, ExoMars has great scientific potential, and its timing relative to the Mars Science Laboratory and the Astrobiology Field Laboratory may prove particularly fortuitous.

Astrobiology Field Laboratory

The Astrobiology Field Laboratory (AFL) mission is conceived as being a highly capable rover derived from the Mars Science Laboratory. Its principal goals would be to assess the biological potential of sites, interpret the paleo-climate record, and search for biosignatures of ancient and modern life. This mission concept postdates the publication of the SSE decadal survey, and it is important to note that its origins are more programmatic than scientific. In 2001, MEPAG was asked to define a Mars exploration strategy that embodied a series of alternative pathways that could be chosen based on anticipated discoveries. In undertaking this task, MEPAG was operating under explicit instructions from the Office of Management and Budget to devise at least one pathway that did not include a Mars sample-return mission. In other words, the AFL was conceived as a scientific response to an anticipated budgetary and political climate that would preclude the return of sample from Mars to Earth in the decade 2011-2020. Despite its origins, an appropriately instrumented AFL has important astrobiological potential as either a stand-alone mission or, with appropriate phasing, as a means to exploit scientific discoveries made by earlier missions. At this writing, the AFL mission is not well enough defined to allow detailed discussion of the astrobiological results that would be obtained.

Mid Rovers

The Mid Rovers are conceived as being more capable than the Mars Exploration Rovers but less complex, costly, and heavy than the Mars Science Laboratory. Their principal purpose is to serve as geological explorers, that is, to evaluate the geological context of specific sites and search for organic compounds at targets identified by prior missions. As currently envisaged, NASA's goal is to fly two rovers for a cost approximately equal to that of the Mars Science Laboratory. The Mid Rovers would be equipped with a modest yet capable payload and utilize an entry, descent, and landing system capable of placing the spacecraft with a landing ellipse <100 km long. This mission concept postdates the publication of the SSE decadal survey.

Mars Long-Lived Lander Network

The Mars Long-Lived Lander Network (ML^3N) is envisaged as a global grid of small landers designed to make coordinated measurements of geophysical and meteorological phenomena for an extended period, possibly several martian years. High-priority objectives for such a network, as outlined in the solar system exploration decadal survey, include the following:[9]

- Determine the planet's internal structure, including its core;
- Elucidate the composition of the surface and near-surface layers and investigate their oxidizing properties;
- Measure the thermal and mechanical properties of the surface;
- Conduct extensive synoptic measurements of the atmosphere and weather;
- Establish the isotopic composition of atmospheric gas and their potential variability; and
- Investigate surface-atmosphere volatile exchange processes.

The geophysical goals would be addressed via passive seismometers and heat-flow probes. The seismic goals will require a minimum of three stations. The meteorological goals can be addressed via measurements of pressure, temperature, relative humidity, atmospheric opacity, and wind velocity. Humidity sensors are particularly important from an astrobiological perspective because they would track the flux of water vapor into and out of the regolith with time of day and season, providing important insight into the water budget on Mars. The meteorological goals would, ideally, require a dozen or more stations distributed so that the maximum distance between any pair of observing sites is no more than a planetary radius. The inclusion of mass spectrometers in instrument packages will permit high-precision, long-lived chemical and isotopic atmospheric analysis of the chemical dynamics of C, H, and O at Mars's surface. Time variability of isotopic compositions can be interpreted in terms of sources, sinks, and reservoirs of volatiles, and atmospheric evolution.

REFERENCES

1. D.J. McCleese (ed.), *Robotic Mars Exploration Strategy: 2007-2016*, JPL 400-1276, Jet Propulsion Laboratory, Pasadena, Calif., 2006.

2. D.W. Beaty, M.A. Meyer, and the Mars Advanced Planning Group, *2006 Update to Robotic Mars Exploration Strategy: 2007-2016*, Unpublished white paper, posted November 2006 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

3. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 84 and 200.

4. NASA, Science Mission Directorate, *A Roadmap for the Robotic and Human Exploration of Mars*, p. ES-3, NASA Headquarters, Washington, D.C., 2005.

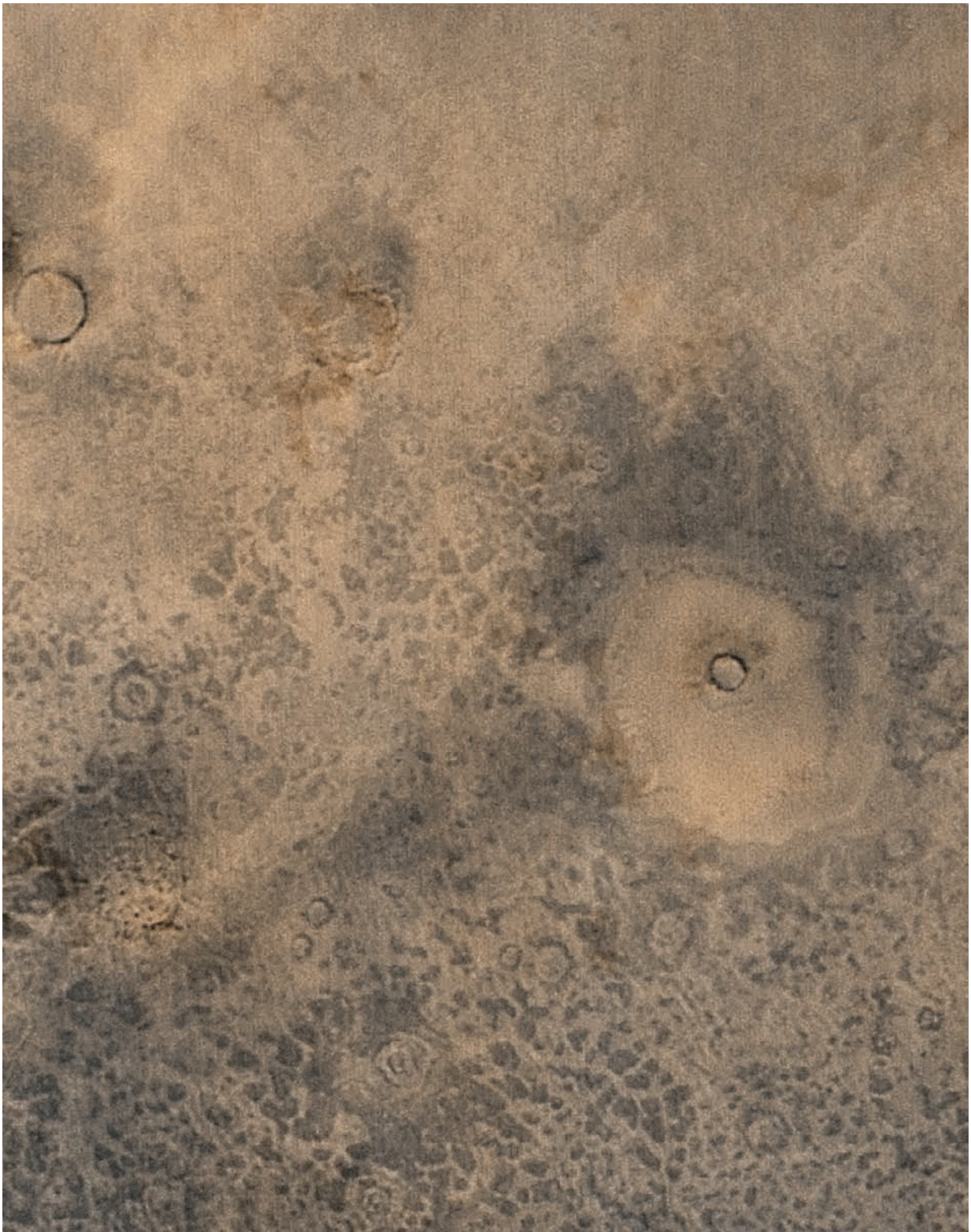
5. National Research Council, *Review of Goals and Plans for NASA's Space and Earth Sciences*, The National Academies Press, Washington, D.C., 2006, p. 11.

6. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 7, 83, 200.

7. MEPAG's study of MSTO is available at <mepag.jpl.nasa.gov/reports/MSTO_SAG_reports.doc>.

8. J. Vago, B. Gardini, G. Kminek, P. Baglioni, G. Gianfiglio, A. Santovincenzo, S. Bayón, and M. van Winnendael, "ExoMars: Searching for Life on the Red Planet," *ESA Bulletin* 126:16-23, 2006.

9. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, p. 7.



7

Planetary Protection for Mars Missions

For the purposes of defining an astrobiology strategy, planetary protection relates to the ability to protect Mars from contamination by life from Earth, as a means of ensuring that future life sciences experiments and analyses will not be compromised. Concerns deal both with introducing organisms from Earth into martian environments in which they might grow and with introducing organisms or organic contamination originating on Earth into environments in which they might be inadvertently mistaken for indigenous martian materials.

COSPAR AND NASA POLICIES

NASA policy and implementation for planetary protection follow COSPAR guidelines. A recent NRC report dealt explicitly with planetary protection, and the committee summarizes briefly the recommendations from that report and the subsequent analyses and interpretations.[1] Within the COSPAR guidelines, the degree of action necessary depends on the nature of the mission. Mars is of particular interest in planetary protection due to its relevance to the processes of chemical evolution that might have led to life, the possible origin or occurrence of life in the past or at present, and the potential for contamination to jeopardize future life-related measurements or experiments. Missions such as flybys or orbiters that are to have no direct contact with the planet are designated as Category III, and landers or probes that have direct contact at the surface are designated as Category IV. The requirements imposed on spacecraft for cleanliness and sterilization depend on the category into which they fall.

Category IV missions are subject to a variety of different planetary-protection requirements depending on the science objectives. Missions searching for extant martian life fall into Category IVb. Missions going to a place where liquid water is present or where the presence of the spacecraft could cause liquid water to be present—termed "special regions"—are Category IVc. Other missions to the surface (generally not investigating life; e.g., the Mars Exploration Rovers) fall into Category IVa.

FIGURE 7.1 This picture of Mars's northern plains shows a relatively young impact crater at the middle-right and fainter, older craters elsewhere. The dark/light background pattern is typical of high-latitude plains. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems. The image covers an area of 168 by 124 km.

SPECIAL REGIONS

The designation of "special regions" for Mars, pertinent to Category IVc, has been addressed by three separate committees. In 2002, COSPAR defined a special region as "a region within which microorganisms from Earth are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant martian organisms."[2] A 2006 NRC report examined the 1992 NRC findings on planetary protection for Mars[3] in light of the new COSPAR guidelines, new data on the survival of extemophiles, and data from orbital and robotic missions.[4] Given the compelling nature of the geochemical and geological role played by liquid water on Mars and the potential that any location on the planet might have surface or near-surface water ice, or might have been in contact with relatively recent liquid water, the 2006 report concluded that all of Mars had to be considered as a special region until further observations and analyses could demonstrate that a particular site was not a special region. In essence, that report designated all of Mars as a planetary protection IVc area, unless the mission was to focus primarily on life detection, in which case category IVb would apply.

A IVc designation would have significant ramifications for Mars exploration, in general, and astrobiology, in particular. In short, any lander or rover visiting the surface would have to accept this designation, with its accompanying stringent bioload-reduction requirements. This would have the effect of adding a substantial financial and technical burden to all future missions to the surface, without regard to the scientific intent or objectives. In response, the Mars Exploration Program Analysis Group (MEPAG) chartered a Special Regions Science Analysis Group (SRSAG) to reexamine the issues in the NRC report.[5] This group's primary objective was fivefold:

- Clarify the terms in the existing COSPAR definition of IVc;
- Establish temporal and spatial boundaries for the definition;
- Define suitable propagation conditions on Mars for microbes originating on Earth;
- Analyze the geological environments on Mars that could potentially exceed these biological threshold conditions; and
- Describe conceptually the spacecraft-induced conditions that could exceed the threshold levels for microbial propagation.

The SRSAG recommended that a location be designated as a special region if propagation of organisms was likely to occur within a 100-year time frame. It reasonably pointed out that life on Earth did not reproduce at temperatures of less than 258 K or at a water activity (a_w) of less than 0.61, and that these conditions were generally not likely to be met on the martian surface absent special geological conditions. To be conservative, the SRSAG adopted a temperature and water activity constraint of $T > 253$ K and $a_w > 0.50$, respectively, as the specific definition of a special region. With this definition in mind, the only areas on Mars that are currently designated as special regions are the polar regions, gullies, and "pasted terrain" that appear to be formed from liquid water, and specific geological environments such as hot springs that might have access to liquid water.

The recommendations of the SRSAG have yet to be formally adopted by NASA and are currently in review by NASA's Planetary Protection Advisory Subcommittee.

TECHNOLOGY FOR PLANETARY PROTECTION

Both the 2006 NRC report and the 2006 MEPAG report indicate that technology development for sterilization, bioburden reduction, and monitoring of bioburden are high priorities in planetary protection. It should be noted that several of the analytical techniques currently under development and mentioned in those documents cannot undergo the heat-sterilization protocols currently used for bioload reduction. For these technologies to be viable, protocols are necessary that ensure that instruments have already been cleaned and sterilized prior to integration onto the spacecraft but after the spacecraft has undergone heat sterilization, that provide for the use of cooling loops to keep critical instruments cool during sterilization; or that ensure that alternatives to heat sterilization are put in place for these technologies to fly.

Technology development is necessary in areas such as the following:

- Low-temperature sterilization techniques, such as microwave plasma and other plasma-ashing techniques;
- Radiation sterilization technologies for whole spacecraft as well as “hot-spot” removal;
- Real-time, non-culture-based systems for monitoring the amount and types of bioload; and
- Means for providing a suitable mineralogical biological and organic clean sample blank for proofing critical sample-handling pathways.

REFERENCES

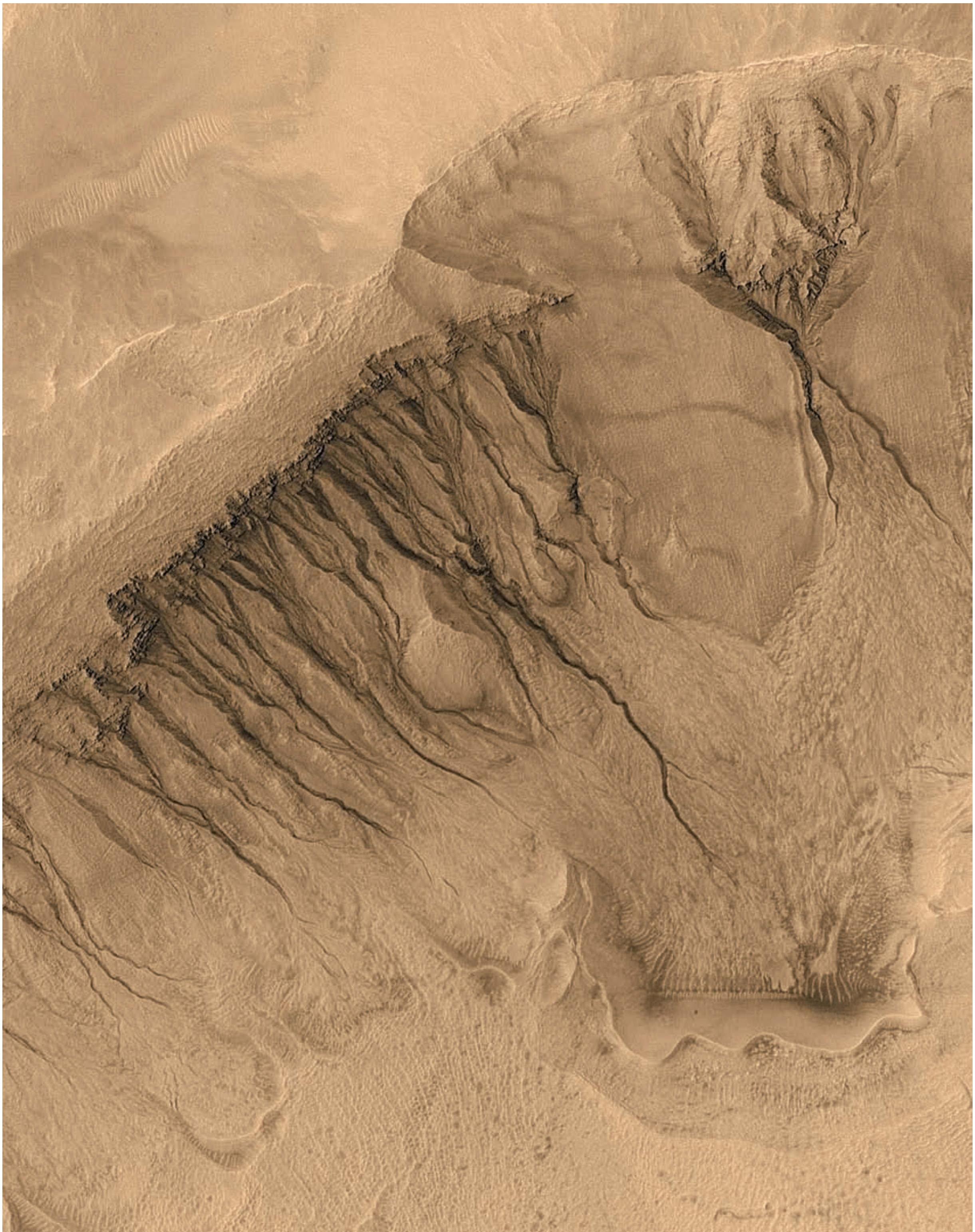
1. National Research Council, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

2. COSPAR, “Report of the 34th COSPAR General Assembly,” *COSPAR Information Bulletin*, No. 156, pp. 24, 67-74, April 2003.

3. National Research Council, *Biological Contamination of Mars: Issues and Recommendations*, National Academy Press, Washington, D.C., 1992.

4. National Research Council, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

5. The MEPAG Special Regions-Science Analysis Group, “Findings of the Mars Special Regions Science Analysis Group,” *Astrobiology* 6:677-732, 2006.



8

Findings and Recommendations

As outlined in the Executive Summary, the committee was charged by NASA to develop an astrobiology strategy for the exploration of Mars which addresses the following topics:

- The characteristics of potential targets for Mars exploration particularly suited for elucidating the prebiotic and possibly biotic history of Mars, and methods for identifying these targets;
- A catalog of biosignatures that reflect fundamental and universal characteristics of life (i.e., not limited to an Earth-centric perspective);
- Research activities that would improve exploration methodology and instrumentation capabilities to enhance the chances of astrobiological discovery; and
- Approaches to the exploration of Mars that would maximize the astrobiological science return.

Before describing the committee's findings and recommendations relating to these four specific areas, it is appropriate to make some general comments about the search for life on Mars

THE SEARCH FOR LIFE ON MARS

Researchers know that life took hold on Earth but do not know if life ever existed anywhere else in the solar system. Mars is the most Earth-like of the other planets and satellites in the solar system, in terms of its geological environment and the availability of liquid water at or near the surface throughout time. It is the most logical place to look for other life and, among places in the solar system that might have life, is the most accessible. The finding of evidence for past or present life would have profound philosophical and scientific repercussions, and a finding either that life was present or that it was not would have dramatic implications for the prospects for life elsewhere in the universe. Because of its compelling importance the search for life should be the main focus of the Mars Exploration Program.

FIGURE 8.1 The gullies at the edge of this crater may have been formed recently by groundwater flowing to the surface from specific horizons. Image from the Mars Orbiter Camera on the Mars Global Surveyor spacecraft courtesy of NASA/JPL/Malin Space Science Systems.

The committee recognizes that life may never have started on Mars or gained a foothold there. However, the search will lead to a broad understanding of the planet as a whole. It requires investigation of the geological and geophysical evolution of Mars, the history of volatiles and climate, the nature of the surface and the subsurface, the history and geographical distribution of liquid water, and the availability of other resources that are necessary to support life, as well as of the processes that controlled each of these. The search also requires a detailed understanding of the nature of terran life and how it functions in different environments.

The Priority of the Search for Life on Mars

Although it is not the only possible emphasis for the Mars program, astrobiology provides a scientifically engaging and broad approach that brings together multiple disciplines to address an important set of scientific questions that also are of tremendous interest to the public. And, more than any other scientific focus, it integrates the disciplines together into a coherent approach to understanding Mars as a planet.

Finding. **The search for evidence of past or present life, as well as determination of the planetary context that creates habitable environments, is a compelling primary focus for NASA's Mars Exploration Program.**

A Broad Approach to the Search for Life on Mars

Addressing astrobiology science goals requires a broad approach to understanding Mars. It involves not just searching for present and past life, but also understanding the geological and environmental context that determines planetary habitability. It will entail determination of the geological and geochemical evolution of the planet, its internal structure, and the nature of its interaction with the space environment. Such an approach will provide the information necessary to be able to apply the results to assessing the potential for life throughout the galaxy. In addition, because of the interconnected nature of the martian geological, geochemical, geophysical, and climatological systems, a broad approach will likely enable astrobiologists to determine which characteristics result from nonbiological processes and which result from biological processes and so could be used as biosignatures. While most aspects of Mars exploration have connections to astrobiology, the emphasis should be on those areas that are most directly related to habitability—the potential for life and the presence of its building blocks, and the possible occurrence of life.

NASA's 1995 report *An Exobiological Strategy for Mars Exploration* took the approach of starting from the global perspective and focusing increasingly on the local perspective. This approach involved a series of steps:

1. Global reconnaissance that focused on the history of water and the identification of sites for detailed in situ analysis;
2. In situ analysis at sites that hold promise for understanding the history of water;
3. Deployment of experiments that address astrobiology science questions, including the nature of martian organic molecules and the presence of features indicative of present-day or prior life;
4. Return of martian samples to Earth for detailed study; and
5. Human missions that would provide the detailed geological context for astrobiology measurements and the detection of modern-day "oases" for life.

This reasoned and measured approach provides the best opportunity for determining the geological and geochemical context in which the most useful and appropriate astrobiological measurements can be determined, implemented, and then properly interpreted and understood. It combines a broad, interdisciplinary approach to understanding Mars as a whole with the detailed, focused investigations that allow researchers to understand the astrobiology of Mars.

Finding. **The search for life and understanding the broad planetary context for martian habitability will require a broad, multidisciplinary approach to Mars exploration.**

Finding. **At the same time, the astrobiological science goals can best be addressed by an implementa-**

tion that allows researchers to address increasingly focused questions that relate to astrobiology goals in particular.

Intellectual Approaches

Applying a broad approach to determining whether life ever existed on Mars will require focusing on the elements most relevant to life, especially carbon. It will be necessary to determine whether organic molecules are present on Mars and where, and which chemical characteristics will allow researchers to distinguish between meteoritic (nonbiological), prebiotic, and biological molecules. In addition, there is still much to be learned about the history and availability of water, and "following the water" is a strategy that researchers will also have to continue to apply.

***Finding.* The very successful intellectual approach of "follow the water" should be expanded to include "follow the carbon," along with other key biologically relevant elements.**

Planetary Protection Considerations

As researchers move toward increasingly detailed examination of the forms in which carbon exists within surface materials, characterization of the nature of possible organic molecules within soil or rock samples, and measurements to search for and identify possible biosignatures, it is clear that contamination by terrestrial materials is a significant concern. Obtaining the desired science results demands that issues related to terrestrial contamination be addressed by appropriate planetary protection approaches. It would be a mistake to have to avoid the sites identified as most promising for scientific discovery because of concerns over planetary protection. NASA must ensure that adequate measures are built into missions from the beginning, incorporating lessons learned from past analyses.

***Finding.* The desire to visit and sample the highest-priority astrobiological sites requires that future surface missions to Mars take the necessary and appropriate planetary protection measures.**

The Importance of Sample Analysis

Useful science analysis of martian surface samples can be carried out either in situ on the martian surface or in terrestrial laboratories with samples returned from Mars to Earth. In situ missions have the advantage of being able to address questions appropriate to specific regions or to obtain measurements of characteristics that might be unstable (e.g., trace chemical species that might represent chemical disequilibrium). In addition, analysis in situ can be done more cheaply than sample-return missions. However, sample return offers the advantages of being able to carry out many more analyses on a sample than can be done in situ, of following up exciting measurements with additional measurements that had not previously been anticipated, and of being able to make measurements or observations using instruments that are not amenable to being accommodated on a lander or rover mission or that were not available at the time of mission development. Indeed, numerous previous studies have consistently pointed out the important contributions that sample-return missions from planetary bodies can make to virtually every area of solar system exploration in general, and to Mars exploration in particular.[1–5] A Mars sample-return mission has thus been an essential component of the Mars exploration strategies advocated by the National Research Council for 30 years.[6–11] Even from the narrower perspective of the search for life on Mars, "evidence" for martian life observed only in situ would create controversy, not conviction. That is, the discovery of past or present life on Mars would be of such importance that it is highly unlikely that the scientific community would be convinced by anything less than the power of laboratory analysis. Therefore, the anticipated astrobiology science results that would be obtained from a sample-return mission are much greater than those that would come from an in situ mission.

***Finding.* The greatest advance in understanding Mars, from both an astrobiology and a more general scientific perspective, will come about from laboratory studies conducted on samples of Mars returned to Earth.**

The astrobiology science goals that have been put forward can be addressed appropriately via a series of robotic spacecraft missions that could be carried out over the next one to two decades. It is critical that any astrobiological evidence that might be present on Mars not be compromised by robotic or human activities before definitive measurements or sample return occur.

Finding. **The scientific study of Mars, including return to Earth of astrobiologically valuable samples that can be used to address the questions being asked today, can be done with robotic missions.**

CHARACTERISTICS OF POTENTIAL TARGET SITES

What are the characteristics of potential targets for Mars exploration that are particularly suited for elucidating the prebiotic and possibly biotic (and postbiotic) history of Mars, and what methods can be used to identify these targets? Current understanding of the environmental requirements for supporting an origin or the continued evolution of life and the nature of the interplay between organisms and their geological and planetary environment is based on our terrestrial example. This understanding informs researchers' views of the types of martian environments that might be fruitful for detailed investigation and the types of individual materials at those sites that might contain pertinent evidence.

Life has the potential to exist in a broad range of environments. Although any place on the surface might provide pertinent information, the most likely places should be explored first. These include places where liquid water might be present today or might have been present for extended periods at some time in the past.

Such sites are pertinent both for searching for evidence of present or past life and for understanding the nature of martian habitability. For present-day or geologically recent water, these sites include the surface, interior, and margins of the polar caps; cold, warm, or hot springs or underground hydrothermal systems; and the source region or outflow region associated with near-surface aquifers that might be responsible for the "gullies" that have been observed. For geologically ancient water, pertinent sites include the source or outflow regions for the catastrophic flood channels, the ancient highlands that formed at a time when surface water might have been widespread (e.g., in the Noachian), and deposits of minerals that are associated with surface or subsurface water or with ancient hydrothermal systems or cold, warm, or hot springs.

Recommendation. **Sites that NASA should target with highest priority to advance astrobiology science objectives are those places where liquid water might exist today or might have existed in the past and where organic carbon might be present or might have been preserved.**

Site Selection

Although the committee anticipates that new measurements are likely to include major discoveries relevant to astrobiology that will point researchers to specific sites, a foundation of data is already available to identify exciting and appropriate sites for either in situ analysis or sample return.

There is no single site that will provide all of the answers pertinent to the astrobiology science goals for Mars. Further, the Mars Reconnaissance Orbiter (MRO) spacecraft is just beginning its mission at this writing, and it will be several years before those results are fully integrated into the (anticipated) revision of our understanding of Mars. Thus, it is premature either to identify a specific landing site for future detailed investigation (either in situ on the surface or as a source of samples for return to Earth) or to limit the range of places that can be visited by spacecraft.

An argument has been made that if only a single sample-return mission is programmatically feasible in the foreseeable future, then it must return the "right" sample from the "right" site, the "right" sample being one that has the best chance for uniquely providing astrobiologically significant information (such as information bearing on the detection of life). The committee disagrees with this viewpoint and argues that there is no such thing as the "right" sample. Any well-selected samples—i.e., samples selected carefully from a thoughtfully chosen site—would provide information that would be incredibly valuable for addressing the scientific goals for the exploration of Mars, in general, and astrobiological goals, in particular. Furthermore, the information necessary to choose an appropriate sampling site is available within existing data sets or data sets whose acquisition is imminent (e.g., those from MRO). Although they cannot be known to identify specific sites as having life, the relevant data do identify sites that have had liquid water or chemical alteration typically associated with liquid water and that have morphologies indicative of the long-term presence of liquid water.

Finding. **Identification of appropriate landing sites for detailed analysis (whether in situ or by sample return) can be done with the data sets now available or imminently available from currently active missions.**

The potential target sites listed above that would important for in situ investigation pertinent to ancient or recent life are at high elevations or at polar latitudes. These include most of the ancient Noachian terrain that would tell researchers about the potential earliest life and polar regions where melting of ice (e.g., at relatively recent epochs of high obliquity) could provide liquid water to sustain life. Accessing these sites will require an increased capability to land at a wider range of latitudes and elevations than are accessible by the Mars Science Laboratory (MSL), for example. Among the requirements are advances in landing site selection and in entry, descent, and landing technologies, and the provision of more capable power systems to ensure spacecraft survival during extended missions in the polar regions. In addition, given the importance of mobility as demonstrated by the Mars Exploration Rover (MER) mission, future rovers should have adequate capability to visit a wide range of geographical and geological terrains on a single mission.

Recommendation. **Future surface missions must have the capability to visit most of the martian surface, including Noachian terrains and polar and high-latitude areas, and to access the subsurface.**

Exposure to strongly oxidizing environments or to high fluxes of radiation is not conducive to the preservation of biologically diagnostic carbon compounds; this knowledge should be factored into decisions about where to collect samples. Terrestrial-based knowledge suggests that fine-grained sedimentary rocks, evaporites, and hydrothermal deposits are examples of rock types that can preserve biosignatures. Inadvertent processing of samples by heating or shock during sampling, or processing prior to in situ analysis or return to Earth, should be avoided.

Recommendation. **Selection of samples for analysis (either in situ or of samples returned from Mars to Earth) should emphasize those having the best chance of retaining biosignatures.**

BIOSIGNATURES

What biosignatures reflect fundamental and universal characteristics of life? Unfortunately, there is no single comprehensive or unique biosignature whose presence would indicate life and whose absence would uniquely indicate the absence of life. Experience from examination of the ALH 84001 meteorite and analysis of evidence relating to claims of the earliest life on Earth have demonstrated that the potential interplay between putative organisms and their geological environment is so complex that researchers may never be able to identify a unique biosignature that would work in all environments and at all times. Rather, the sum total of all measurements on a sample, in the context of understanding of the origin and evolution of the martian environment, will be required. What has been learned from the study of Earth's earliest life and of the interplay between organisms and their planet, as well as from modern biology, provides the most appropriate guide to selecting targets on Mars and searching for biosignatures.

Of all the various life-detection techniques available, analysis of carbon chemistry is the first among equals. Organic analysis is likely to provide a more robust way to detect life than imaging technologies, mineral assemblages, isotopic measurements, or any one other single technique. This is the case because, on Earth, the patterns of biogenic carbon compounds reflect organized polymerization of smaller subunits, or precursors, and comprise mixtures with a limited range of atomic spatial arrangements very different from those made by abiological processes. However, organic analysis alone is insufficient to detect life. An ensemble of all of the relevant methodologies, combined with analysis of geological and environmental plausibility, will likely provide the best evidence for the presence or absence of life in a sample; there is no single, unique characteristic that would allow researchers to identify a region that might now have, or might once have had, life, or to determine whether life is, indeed, indicated.

Recommendation. **The lack of a comprehensive understanding of all of the potential biosignatures for Mars exploration means that NASA should employ a combination of techniques that utilize both Earth-centric and non-Earth-centric approaches that focus on the basic concepts in carbon chemistry, imaging, mineral assemblages, and isotopic measurements.**

Specific aspects of carbon chemistry that should be investigated include the following:

- The presence of polymers based on repeating universal subunits;
- Patterns in the carbon isotopic compositions of organic molecules that reflect organized polymerization of smaller subunits or precursors;
- Patterns in the carbon numbers of organic compounds; and
- The presence of carbon compounds that have only a subset of the possible connectivities or atomic spatial arrangements (i.e., just a few structural isomers or stereoisomers and/or strong chiral preferences).

EXPLORATION METHODOLOGIES AND INSTRUMENTATION

What research activities would improve exploration methodology and instrumentation capabilities to enhance the chances of astrobiological discovery? The vitality of Mars astrobiology science goals and investigations has not diminished with the delays in a Mars sample-return mission or the initiation of other activities. The ongoing missions (e.g., Mars Odyssey, Mars Express, Mars Exploration Rovers, and Mars Reconnaissance Orbiter) and the missions in development (Phoenix and Mars Science Laboratory) all are, or will be, returning scientific data that directly address astrobiology goals in substantive ways. Missions that are being planned for the next decade also have strong astrobiology components, and the Mars program is intimately intertwined with astrobiology science objectives. Thus, if astrobiologists are to advance their science goals for the exploration of Mars, they must work with NASA to ensure that the upcoming missions proceed as scheduled and, then, take advantage of the scientific data these spacecraft will collect.

Ensuring the success of future missions will require attention to the following activities:

- Technology development,
- Research and analysis activities, and
- Supporting activities such as studies of martian meteorites and Mars-analog environments on Earth.

Technology Development

Missions such as Mars Sample Return and the Astrobiology Field Laboratory will require significant technical advances if they are to be carried out successfully. Technology development must occur both in mission-related areas (e.g., entry, descent, and landing systems, including a precision landing capability; sample-return technology; in situ sample processing and handling; and planetary protection) and in astrobiological science instrumentation (so that the necessary next generation of instruments is ready to go). In particular, a means must be developed to take instruments from the low and middle technology readiness levels[a] up to TRL 6 so that they are ready for flight when needed.

Recommendation. **The Mars Exploration Program must make stronger investments in technology development than it does currently.**

Research and Analysis Activities

It is through the basic research and analysis (R&A) programs that results are obtained from the data returned by missions and ideas are developed for future missions. In particular, R&A programs are the primary vehicle by which the Mars Exploration Program can maintain its vitality in response to new discoveries. R&A programs should include analysis of existing and about-to-be-obtained data from Mars missions, analysis of basic martian processes to help in developing ideas about Mars evolution and history, and comparative planetology that allows

[a]NASA measures progress primarily by using technology readiness levels (TRLs) with each plan and providing a technology maturation plan with TRL milestones aligned with cost estimates for achievement. The higher the TRL, the more mature the technology. Technology program performance is measured as a function of planned versus actual TRL advancement.

a better understanding of environmental processes on each planet. In addition, R&A programs also must address the need for basic understanding of the interplay between organisms and their geological environments, the nature of biosignatures, and the astrobiology of Mars.

In addition to preparing for the next generation of missions and the science objectives to be addressed by them, ongoing analysis and investigation put the science community in a better position to understand the nature of the questions that are being asked or the results that are being obtained. Because the education and the training of scientists, engineers, and managers who will work on the next generation of missions are funded through the R&A and technology programs, the health of those programs is vital to the development of a future workforce.

Recommendation. **Continued strong support of NASA's basic research and analysis programs is an essential investment in the long-term health of the Mars Exploration Program.**

Studies of Martian Meteorites and Mars-Analog Environments

Analysis of martian meteorites has been central to the development of the current understanding of Mars, its potential for life, and ideas about detection of present or fossil life. It continues to be essential to developing ideas and protocols relevant to analyzing samples that are pertinent to astrobiology and life-detection science goals. It is especially important to search for martian meteorites that formed during early periods of Mars's history, as well as meteorites of sedimentary origin. This is an important area of collaboration between NASA and the National Science Foundation.

Recommendation. **Collection and analysis of martian meteorites must continue, even though biases in the compositions and ages of these meteorites, their uncertain provenance, and the effects of impact-ejection and transfer to Earth mean that they cannot take the place of samples returned from Mars.**

As with the analysis of martian meteorites, studies of Mars-analog sites are essential to mission development and execution and to the training of the scientists engaged in current and future missions. Such studies focus on the technological aspects of missions and not on the development of basic scientific concepts regarding how life behaves and leaves signatures. Studies of Mars-analog sites on Earth should continue to be a fundamental aspect of Mars astrobiological research because they provide critical understanding of Mars-like environments for the testing and development of instrumentation and sample-handling protocols; understanding that supports the development and validation of techniques for detecting and measuring biosignatures, including establishing baseline abiotic signatures; and discovery of novel organisms and metabolisms and the chemical/isotopic imprints of these metabolisms on Mars-like environments.

Recommendation. **Terrestrial analog studies should include testing instrumentation, developing techniques for measuring biosignatures under Mars-like conditions, and conducting technological proof-of-concept studies.**

MAXIMIZATION OF SCIENCE

What approaches to the exploration of Mars will maximize the astrobiological science return? The astrobiology science goals for Mars are extremely broad. They legitimately include determining the volatile inventory of the planet upon formation and the evolution of volatiles through time, the geological and geophysical evolution of the planet, the interplay between the geology and the atmosphere and the history of habitability, and, of course, the determination of whether there is life today or has been life at some time in the past. As researchers learn more about Mars, they are finding that there is an incredible diversity of local and regional environments—as exemplified by the landing site of the rover *Opportunity*—that have chemical properties and physical implications that are very different from what had been expected. There clearly is the potential for identifying an incredibly diverse range of properties as more is learned about more places in detail via remote sensing and in situ analysis. Thus, any astrobiological exploration of Mars has to take into account the incredible diversity of Mars, as well as the diversity of questions that bear on the issues.

Sample Return Is Essential

Although almost any measurements made at Mars provide information that is pertinent to astrobiology, the value of having an astrobiology science strategy is in being able to prioritize the possible measurements and the missions that can make them in order to provide useful scientific guidance.

The approach outlined in NASA's 1995 report *An Exobiological Strategy for Mars Exploration* involved missions of increasing capability and focused on astrobiology-related issues. In the intervening decade, NASA has carried out a program of orbital reconnaissance and in situ analysis to understand the role of water. Similarly, missions are in development (e.g., Phoenix and Mars Science Laboratory) that will explore the chemistry and the biological potential of the surface in detail. With this information in hand, and following that approach, analysis of samples returned from Mars to Earth will yield the greatest increase in our understanding of Mars and thus support for addressing astrobiology science goals as well as science goals related to other aspects of Mars. A commitment to carrying out a Mars sample-return mission is necessary to ensure that such a mission does not continue to be pushed farther into the future.

Samples collected for return to Earth should include a well-chosen suite of materials collected from a diverse set of locations by a capable rover, and should include both weathered and unweathered materials with minimal thermal and shock histories. Given the MER experience and current understanding of the nature of materials on the martian surface, a "grab sample" obtained from a stationary lander is not likely to be sufficient to provide the necessary data.

Finding. **Sample return should be seen as a program that NASA and the Mars science community have already embarked upon rather than as a single, highly complex, costly, and risky mission that is to occur at some future time.**

As an example, the committee notes that technology development pertinent to sample return (e.g., sample handling and packaging, Mars ascent vehicle, precision landing, planetary protection, and so on) has been ongoing but needs to move forward in earnest immediately so that the necessary technology will be available in a timely manner. There is a significant heritage from ongoing Mars missions (such as MER and MSL) that will carry over to the implementation of Mars Sample Return; from sample-collection missions such as Stardust and Genesis; and from the heritage of sample planning and analysis conducted over the last two decades.

Programmatically, sample return should be phased over multiple launch opportunities. A first phase could involve caching samples on Mars; a second phase, putting samples into orbit; and a third phase, returning samples to Earth. This approach would also allow some independent science investigations at each phase that would continue to engage the science community and the public, and it would increase resilience of the program in the face of the failure or delay of individual spacecraft missions.

However, the program's emphasis should be on sample return. Missions subsequent to MSL should emphasize science, technology, and programmatic issues that lead directly to sample return, and return of samples to Earth should be carried out at the earliest opportunity.

Recommendation. **The highest-priority science objective for Mars exploration must be the analysis of a diverse suite of appropriate samples returned from carefully selected regions on Mars.**

Sample Caching

As part of an effective sample-return strategy, sample caching could be carried out by each surface mission, utilizing a minimalist approach so as not to make sample caching a cost- or technology-driver. That is, caching should not be made so complicated as to preclude actually carrying it out. Because researchers cannot predict with confidence which landing sites might provide astrobiologically interesting samples, samples should be cached from all visited sites. This strategy should allow collection of diverse samples and mitigate the costs of sample-return missions. It is, of course, dependent on the development of a precision landing capability.

Recommendation. **If it is not feasible to proceed directly toward sample return, then a more gradual approach should be implemented that involves sample caching on all surface missions that follow the Mars Science Laboratory, in a way that would prepare for a relatively early return of samples to Earth.**

Alternative Strategies

Despite the compelling scientific arguments for the return of martian samples to Earth and irrespective of how such an endeavor is implemented, sample return will be a technically challenging, high-risk, high-cost endeavor. Although the committee was not composed appropriately to independently estimate the cost of such a mission, figures in the range of $3 billion to $5 billion are frequently quoted.[12] Thus, the decision to implement such an undertaking would have an impact on NASA's science program extending far beyond the Astrobiology Program or the Mars Exploration Program. As such, the decision to implement a Mars sample-return mission will hinge on factors such as the relative balance of NASA's flight activities between the various scientific programs, the state of the agency's budget, and opportunities presented by international cooperation—all factors whose examination is beyond the scope of this study. As such, it behooves the astrobiology community to plan for the possibility that a Mars sample-return mission is not an integral component of current mission plans.

If a commitment is not made for sample return, then high-quality and high-priority science still can be done at the surface of Mars, for example from an astrobiology field laboratory. Such an advanced rover mission should have significant analytical capabilities beyond those of MSL and should address science questions complementary to those of MSL. Alternatively, two Mid Rovers could investigate the geological and geochemical diversity of carefully selected sites on Mars. Either approach would provide high science value and would be compelling in itself.

Although a compelling Astrobiology Field Laboratory (AFL) mission could be defined today that would complement MSL, the launch of an AFL mission should be phased to take into account the results obtained from MSL. Such a mission would be most effective as part of an overall program that also addressed the broad range of issues related to astrobiology, including planetary habitability. However, it must be recognized that, although they would address some astrobiology science goals, such missions would have a much more limited ability than sample return to make fundamental discoveries and to respond to them. They would be incapable of addressing the most fundamental astrobiology and other science goals in the same substantive ways as sample return. An AFL mission would be complementary to a sample-return mission in that it would allow some extension of the detailed results from sample return to other locations via in situ analyses.

International Cooperation

International collaboration in Mars missions has the potential to make expensive missions such as Mars Sample Return affordable. The benefit, however, has to be balanced against the political difficulties of working with multiple countries and multiple space agencies. The European Space Agency (ESA), for example, already values the role that astrobiology plays in Mars science. One area of relatively straightforward collaboration would involve encouraging ESA to include a sample-caching capability on its rovers currently under development that would be analogous or equivalent to that being encouraged by this committee for NASA rovers.

Recommendation. **International collaboration in Mars missions should be pursued in order to make expensive missions affordable, especially in the areas of sample caching and sample return.**

REFERENCES

1. See, for example, M.J. Drake, W.V. Boynton, and D.P. Blanchard, "The Case for Planetary Sample Return Missions: 1. Origin of the Solar System," *Eos* 68:105, 111-113, 1987.

2. See, for example, J.L. Gooding, M.H. Carr, and C.P. McKay, "The Case for Planetary Sample Return Missions: 2. History of Mars," *Eos* 70:745, 754-755, 1989.

3. G. Ryder, P.D. Spudis, and G.J. Taylor, "The Case for Planetary Sample Return Missions: 3. The Origin and Evolution of the Moon and Its Environment," *Eos* 70:1495, 1505-1509, 1989.

4. T.D. Swindle, J.S. Lewis, and L.A. McFadden, "The Case for Planetary Sample Return Missions: 4. Near-Earth Asteroids and the History of Planetary Formation," *Eos* 72:473, 479-480, 1991.

5. National Research Council, *Assessment of Mars Science and Mission Priorities*, The National Academies Press, Washington, D.C., 2001, pp. 83-88.

6. National Research Council, *Strategy for the Exploration of the Inner Planets: 1977-1987*, National Academy of Sciences, Washington, D.C., 1978.

7. National Research Council, *Update to Strategy for Exploration of the Inner Planets*, National Academy Press, Washington, D.C., 1990.

8. National Research Council, *International Cooperation for Mars Exploration and Sample Return*, National Academy Press, Washington, D.C., 1990, pp. 1, 3, and 25.

9. National Research Council, *An Integrated Strategy for the Planetary Sciences: 1995-2010*, National Academy Press, Washington, D.C., 1994.

10. National Research Council, *Review of NASA's Planned Mars Program*, National Academy Press, Washington, D.C., 1996, pp. 3, 26, and 29.

11. National Research Council, *Assessment of Mars Science and Mission Priorities*, The National Academies Press, Washington, D.C., 2001, pp. 3, 83-88, and 99-102.

12. In March, 2007, J. Douglas McCuistion, the director of NASA's Mars Exploration Program, informed the NRC's Committee to Assess Solar System Exploration that cost estimates for a Mars sample-return mission run the gamut from $3 billion to $10 billion, with $5 billion being most likely. Also see, National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006, p. 19, note 26.

Appendixes

A

Martian Features Mentioned in Text

Argyre Planitia—A large impact basin (50°S, 318°E) in the southern highlands. Several channels enter the basin, suggesting that it may have once contained a lake. Numerous esker-like ridges (former sites of subglacial channels) on the floor of the basin support the supposition that a lake was formerly present that froze.

Ceraunius Tholus—A 100-km-diameter, 6-km-high volcano (24°N, 263°E) in Tharsis. The dense channeling on its flanks has variously been attributed to ash flows, rainfall, and melting of snow. A large channel that starts at the summit and leaves a delta at its terminus may have resulted from melting of snow in the summit crater by volcanic heat.

Cerberus Fossae—NNW-SSE trending graben (10°N, 157°E) to the southeast of Elysium. The graben has been the source of floods of both water and lava. Crater dating suggests that some floods may be as young as 10 million years before the present. Water from the graben may have pooled in the Cerberus plains to the southeast of the graben.

Chryse Basin—A low area (20°N, 320°E) to the east of the Valles Marineris into which converge several of the largest outflow channels on the planet. It was chosen as the landing sites for both Viking 1 and Pathfinder because of the abundant evidence for water erosion.

Columbia Hills—A group of hills (14.6°S, 175.5°E) to the southeast of Mars Exploration Rover *Spirit*'s landing site dedicated to the seven astronauts from the space shuttle *Columbia*. The rocks of the hills are highly variable both in their origin and in their degree of alteration, ranging from unaltered, olivine-rich rocks that retain all their primary volcanic minerals to sulfate-rich, hydrated mineral-rich rocks with almost no primary minerals remaining.

Echus Chasma—A north-south box canyon (5°N, 280°E) located north of the Valles Marineris. It is closed to the south and open to the north. The canyon may have been the source of the floods that formed Kasei Vallis, the largest outflow channel on the planet.

Elysium—The second largest volcanic region on the planet centered at 25°N, 145°E.

Gusev crater—A 60-km-wide impact crater (14.6°S, 175.5°E) in which the Mars Exploration Rover *Spirit* landed. The southern rim of the crater is breached by a large channel, Ma'Adim Vallis, thought to have formed by a large flood. A lake may have temporarily formed in the crater at the time of the flood, although *Spirit* found no evidence for such a lake.

Hecates Tholus—A 180-km-wide, 8-km-high volcano (32.1°N, 150.2°E) in Elysium with slopes densely dissected by narrow channels. The channels have been attributed to melting of snow by volcanic heat, possibly accompanied by hydrothermal circulation.

Hellas—A large, deep impact basin (40°S, 70°E) within the southern uplands that contains the lowest point on the planet (–9.2 km). The basin is one of the oldest topographic features of the planet, having formed deep within the era of heavy bombardment. If early Mars was warm and wet, as suggested by the widespread dissection of the oldest terrains, then Hellas would formerly have contained a large lake or sea.

Holden crater—A 140-km-diameter impact crater (27°S, 326°E) in the southern highlands. The crater has well-developed deltas on its floor at the ends of channels that breach the crater rim.

Meridiani Planum—An almost level plain (0°N, 355°E) on which the Mars Exploration Rover *Opportunity* landed in 2004. Beneath the plain is a kilometers-thick sequence of bedded sediments that appears to rest on an older, more cratered basement.

Nanedi Vallis—A large branching valley (5°N, 310°E) similar to Nirgal Vallis but located in Xanthe Terraat.

Nirgal Vallis—A large branching valley (28°S, 320°E) that is younger in age than typical branching valleys in the cratered uplands. Its characteristics suggest an origin by groundwater sapping rather than surface runoff. Gullies on its walls may indicate recent water-abetted slope failure.

Noachian uplands—Heavily cratered terrain that has survived from the era of heavy meteorite bombardment that ended around 3.7 billion years ago. The surface is heavily dissected by branch valley networks, which suggest warmer climatic conditions when the terrain formed. The rocks of Columbia Hills may be representative of what composes the terrain.

Olympus Mons—Roughly three times taller than Mount Everest, Olympus Mons (17°N, 225°E) is the tallest known volcano in the solar system. It probably grew slowly over almost the entire life of the planet by massive eruptions of basaltic lava widely spaced in time.

Tharsis—A volcanic province, roughly 3,500 km across, centered on the equator at 250°E, and containing some of the largest volcanos in the solar system. The province has been a center of volcanism for almost the entire history of the planet. The massive volcanic pile was already in place at the end of heavy bombardment 3.7 billion years ago, and activity has continued ever since.

Valles Marineris—A vast system of interconnected canyons more than 4,000 km long, and up to 600 km wide and 10 km deep. The canyons formed by faulting but have been substantially modified by other processes such as water erosion and mass-wasting. They contain thick sequences of sulfate-rich sediments. The canyon may have formerly contained lakes that drained catastrophically to the east.

B

Glossary

Alkanes—Saturated hydrocarbons having the general formula C_nH_{2n+2}, where n is an integer >0. Examples include methane (CH_4) and propane (C_4H_{10}).
Amazonian—The geological epoch on Mars dating from some 3 billion years ago to the present day. Regions formed in this period have relatively few impact craters.
APXS—Alpha Proton X-ray Spectrometer.
ASTEP—Astrobiology Science and Technology for Exploring Planets.
ASTID—Astrobiology Science and Technology Instrument Development.
Astrobiology Field Laboratory (AFL)—NASA's proposed fourth-generation Mars rover (following on from Mars Pathfinder's *Soujourner*, the Mars Exploration Rovers *Spirit* and *Opportunity*, and the Mars Science Laboratory). As currently conceived, this rover is a candidate for launch in 2016 or 2018. It will be broadly similar in mass, size, and payload capacity to the Mars Science Laboratory. But it will be equipped with a different set of scientific instruments, possibly ones focusing on life detection.

BIF—Banded iron formation, 2 billion- to 3.5 billion-year-old banded rock consisting largely of chert and iron minerals.
Biosignatures—A variety of indicators (e.g., chemical, morphological, mineralogical, isotopic) that support the possible existence of past life.

Carbonaceous chondrite—A type of stony meteorite that is rich in carbon compounds and is thought to be relatively unaltered since the beginning of the solar system. The bulk elemental composition of these chondrites is believed to resemble that of the material from which the solar system formed.
ChemCam—An instrument under development for the Mars Science Laboratory. It utilizes a laser system for spectroscopic analysis and microimaging.
Chemolithoautotrophs—Organisms deriving all of their carbon and energy requirements from inorganic compounds.
Chiral—Describing a molecule configured such that it cannot be superimposed on its mirror image.
CHNOPS—Carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur; the most important biogenic elements.
COEL—Committee on the Origins and Evolution of Life.
CRB—Columbia River Basalt.

Diastereoisomers—Stereoisomers that are not mirror images of each other.

Electrophoresis—A chemical analysis technique that takes advantage of the differential movement of a charged substance under the influence of an electric field.

Enantiomers—Stereoisomers that are mirror images of each other. Enantiomers are optically active and rotate the plane of polarized light.

Epimer—A stereoisomer that has a different configuration at only one of several chiral carbon centers.

Extremophiles—Microorganisms capable of growing under extreme physiochemical conditions, such as high temperatures, pressures, and acidity.

Fischer-Tropsch (FT) process—A method for the synthesis of hydrocarbons and other carbon compounds. Typically, a mixture of hydrogen and carbon monoxide is reacted in the presence of an iron or cobalt catalyst to produce methane and other organic compounds, with water and carbon dioxide as by-products.

GC-MS—Gas chromatography-mass spectrometry.

Graben—A block of the crust, generally with length much greater than its width, that has dropped relative to the areas on either side because it is bordered by two faults.

GRS—Gamma-Ray Spectrometer.

HEND—High-Energy Neutron Spectrometer.

Hesperian—The martian geological epoch ranging from some 3.7 billion to 3 billion years ago. Regions that were formed in this era are characterized by extensive lava fields.

Isomer—One of two or more substances that have the same chemical composition but differ in structural form.

Kerogens—A family of chemical compounds that make up a portion of the organic matter found in sedimentary rocks. They are insoluble in organic solvents, non-oxidizing acids (HCI and HF), and bases because of their very high molecular weight. Each kerogen molecule is formed by the random combination of numerous monomers. When heated, hydrogen-rich kerogens yield crude oil, and hydrogen-poor kerogens yield mainly gas.

Labile—Easily reactive.

LC-MS—Liquid chromatography-mass spectrometry.

Macromolecules—Molecules with a high molecular mass, such as polymers.

Mars Express—A European Space Agency mission comprising an obiter mapping the surface and atmospheric composition and an unsuccessful lander, the Beagle 2. Mars Express has been orbiting Mars since late 2003.

Mars Odyssey—A NASA spacecraft launched in 2001. Odyssey is an orbiter looking for evidence of past or present water and mapping the mineralogical characteristics of the martian surface.

MAVEN—The Mars Atmosphere and Volatile Evolution mission, one of two candidates under consideration by NASA for the Mars Scout launch opportunity in 2011.

MEPAG—NASA's Mars Exploration Program Analysis Group.

MER—NASA's Mars Exploration Rover mission, which launched two rovers, *Spirit* and *Opportunity*, in 2003. Both rovers are equipped to image and analyze the martian landscape.

Metazoa—Multicellular organisms capable of locomotion.

Metaphytes—Multicellular plants.

MGS—NASA's Mars Global Surveyor spacecraft, which has been orbiting Mars since 1996. Although the spacecraft completed its primary mission of mapping the martian surface in 2001, it continued to return important scientific data until it lost contact with Earth in November 2006.

Mid Rovers—A proposed Mars rover mission currently being studied as a candidate for launch in 2016 or 2018.

These rovers are currently conceived as being more capable than the Mars Exploration Rovers but less complex, costly, and heavy than the Mars Science Laboratory.
Miller-Urey Experiment—The 1953 experiment testing the possibility of constructing organic compounds using a spark of electricity and inorganic molecules such as water, methane, ammonia, and hydrogen. The experiment showed that it is possible to form some of the building blocks of life without life present to synthesize them.
MRO—A NASA spacecraft launched to Mars in 2005. It began relaying high-resolution images and other scientific data in 2006. It is currently laying the groundwork for future missions by analyzing weather, surface conditions, landforms, ice, and possible landing sites.
MSL—Mars Science Laboratory, a NASA mission scheduled for launch in 2009. MSL is a rover significantly larger than the Mars Exploration Rovers and capable of carrying a comprehensive payload of advanced scientific instruments.
MSTO—Mars Science and Telecommunications Orbiter, a proposed NASA mission currently scheduled for launch in 2013. Its primary goals are to study the martian atmosphere and climate and to provide communications infrastructure to future missions.

NADPH—The reduced form of nicotinamide adenine dinucleotide phosphate
Noachian—The earliest identified martian geological epoch. It spans the period from some 4.1 billion to 3.7 billion years ago. Regions from this epoc are heavily marked with impact craters. These regions were subject to extensive flooding by liquid water late in the period.
NS—Neutron spectrometer.
Nuées ardentes—Clouds of incandescent, gas-charged ash that flow down the sides of an erupting volcano at high speeds.

Obliquity—The angle between the orbital plane of an object and its equatorial plane.
OMEGA—The visible and infrared mineralogical mapping spectrometer on the Mars Express.
Phoenix—A NASA Mars lander mission scheduled for launch in 2007. Phoenix will look for evidence of water and possible habitats for microbial life on Mars.
Photolysis—The decomposition of a chemical substance into simpler units as a result of the action of light.
Phyllosilicates—A family of minerals featuring parallel sheets of silicate. Examples include clays, mica, and serpentine.
Pinpoint landing—Generally speaking, the landing of a spacecraft on a planet's surface within a few hundred meters of a pre-selected point.
Polycyclic aromatic hydrocarbons (PAHs)—A class of very stable organic molecules made up of only carbon and hydrogen. These molecules are flat, with each carbon having three neighboring atoms, much like graphite. They are a standard product of combustion.
Precision landing—Generally speaking, the landing of a spacecraft on a planet's surface within 10 km or so of a pre-selected point.
Psychrophiles—Organisms that have a maximum growth temperature of 20°C, an optimal growth temperature of 15°C or lower, and a minimum growth temperature of 0°C or lower.
Pyrolysis—The breakdown or destruction of a molecule caused by heat.

R&A—Research and analysis.
Racemic compound, racemic mixture, racemate—An equimolar mixture of the two enantiomeric isomers of a compound. As a consequence of the equal numbers of levo- and dextro-rotatory molecules present in a racemate, there is no net rotation of the plane of polarized light.
Radiolysis—The breakdown of a molecule as a result of ionizing radiation.
Raman spectroscopy—A technique for determining the composition a material by measuring the change in energy of light scattered off the material.
Regolith—The layer of fragmented, incoherent rocky debris on the surface of a planetary body.

Respiration—The process by which the chemical bonds of energy-rich molecules such as glucose are converted into energy usable for biological processes.

Serpentinization—A metamorphic process in which ultrabasic rocks react with water to create a variety of hydrous, magnesium-iron phyllosilicate minerals known collectively as serpentine. The process is endothermic and results in the liberation of hydrogen, methane, and hydrogen sulfide.

SLiME—Subsurface lithoautotrophic microbial ecosystem.

SNC meteorites—The family of shergottite, nakhlite, and chassignite stony meteorites believed to have originated on Mars.

SRB—Sulfate-reducing bacteria.

Stereoisomers—Isomers that differ only in the arrangement of their atoms in space.

Stratigraphic horizon—A layer within a planet's crust that formed in a specific geological epoch.

Strecker synthesis—The synthesis of α-amino acids by the reaction of an aldehyde or ketone with a mixture of ammonium chloride and sodium cyanide followed by acid hydrolysis of the amino nitriles formed.

Stromatolites—Lithified sedimentary growth structures formed by the trapping of sedimentary grains by microorganisms.

Tholins—Complex polymeric substances formed on the surfaces of the icy bodies of the outer solar system by the irradiation of organic compounds. The arrival of these compounds on comets could provide the basic building blocks of life.

TRL—Technology readiness level, a measure of the technical maturity of an instrument or mechanism. The higher the TRL, the more mature the technology.

C

Objectives for Developing a Further Understanding of Biosignatures

The 2001 workshop on biosignatures organized by the NASA Biomarker Task Force established comprehensive objectives for developing a better understanding of biosignatures. These objectives represent an important starting point for future discussions. But, unfortunately, the results of the task group's deliberations were never published in full. To correct this omission, the task group's objectives are reproduced below:[a]

- Improve knowledge of recalcitrant biochemicals (those that are resistant to geological degradation) that are produced by bacteria and archaea. Many new organisms are identified on the basis of r-RNA sequences for which we have no knowledge of the lipid or other biomarker compositions.
- Develop and test of immunological or other tagging methods for recognition of specific organic biomarkers that might be more sensitive than mass spectrometry.
- Improve understanding of hydrocarbon distributions produced by abiogenic synthesis (FT, tholins) especially with regard to PAHs and alkanes.
- Measure experimentally both the magnitude of isotopic discrimination and the key factors that control it during isotopic exchange reactions involving metals utilized by biota. Explore effects of important parameters such as pressure, temperature, and composition of the exchanging medium.
- Broaden the database of measured isotopic discrimination by microbiota. Measurements are needed for a broad array of carbon-fixing enzymes (e.g., RUBISCO, PEP-carboxylase). Enzymes that affect the discrimination of sulfur, nitrogen, and biologically important metals are largely unstudied and thus merit investigation.
- Characterize how microbial ecosystem processes can modify the expression of stable isotopic discrimination by the constituent biota. Understand how isotopic patterns observed among the fossilizable products of an ecosystem can help to characterize the biota, their mutual interactions, and also the effects of environmental parameters such as concentrations of key solutes, temperature, and the nature and availability of energy sources.
- In ancient, yet well-characterized fossiliferous rocks, catalog the diversity of the isotopic compositions of both microfossils and minerals (e.g., carbonates, sulfides, etc.) affected by biological processes. The source(s) of this variability should be defined.
- Characterize the nature and extent of post-depositional alteration (by thermal processes, etc.) of minerals

[a]Michael Meyer, NASA Science Mission Directorate, personal communication, 2006.

and biogenic features at the submicron scale. Understand the relationship between metamorphic grade and isotopic patterns among minerals and organic carbon, as a basis for assessing the syngenicity of these components.

- In order to utilize isotopic data for coexisting minerals as indicators of environmental conditions (e.g., temperature of mineral formation), establish criteria for determining whether measured isotopic patterns reflect kinetically controlled versus thermodynamically equilibrated reactions. Can such estimates of environmental conditions be achieved by analyzing coexisting phases at the millimeter to submicron scale?
- By analyzing isotopic compositions of minerals formed in the surface environment, characterize the range of isotopic compositions (e.g., for carbon, nitrogen, and sulfur) witnessed by the environments in which the martian meteorites were formed. This analysis will help to define the background "noise" of isotopic variability against which an isotopic signal of life might ultimately have to be discerned.
- Document the range and systematics of isotopic compositions associated with habitable subsurface environments, including hydrothermal systems. Can "abiotic" versus "biotic" patterns be resolved? Document the ancient fossil record of subsurface life on early Earth.
- Assess the isotopic consequences of aqueous alteration of rocks over a wide range of water/rock ratios, particularly low ratios. An essential objective will be to characterize the nature and extent of the aqueous alteration of the martian crust.
- Improve knowledge about processes that alter the fidelity of morphological biosignatures during and after fossilization. Emphasis should be placed on comprehensive taphonomic and diagenetic studies of extreme ecosystems of relevance to potentially important Mars biotopes. These would include hydrothermal systems (volcanogenic and impact-related), evaporative basins, dry valleys (hot and cold), and subsurface aquifers.
- Experimental studies are required in order to further characterize abiotically produced morphological mimics of microorganisms.
- Interlaboratory evaluation of samples that contain various morphological biosignatures would also help refine criteria for detecting/assessing morphological biosignatures.
- Before mineralogical biosignatures can be determined for small quantities of martian minerals, the database of unambiguous terrestrial biomineralogical signatures must be greatly expanded.
- It is also essential to consider how mineral-based biosignatures change due to heat, time, and other factors (phase transformation, particle morphology evolution). Specifically, the morphological consequences of crystal growth and transformation to other stable, and possibly anhydrous, phases (e.g., hematite, and magnetite) are required. BIF formations are prevalent on Earth but we don't have criteria that unequivocally demonstrate that such deposits preserve life signatures.
- Much work remains to be done in cataloging shapes and compositions of submicron magnetites, and terrestrial analogs.
- Characterization of sulfide minerals and morphologies together with reliable information about the thermal history of the specimen is needed to provide useful information about possible bacterial origin of Fe sulfides in extraterrestrial samples. Explicit consideration of probable differences between Mars hydrothermal geological and Earth geological systems is required.
- Potential biosignatures should be evaluated by means of a systematic testing program utilizing extraterrestrial materials, such as some of the large number of unstudied meteorites. This should include the use of martian meteorites to hone sample-handling and life-detection techniques.
- Methods need to be refined for the characterization and quantification of contamination of returned samples, utilizing, among other approaches, the use of highly characterized witness plates, screening of all materials and methods employed with returned samples, deliberate contamination experiments, and standardization of quality control.

Objectives for flight experiments relevant to biosignatures and prebiotic chemistry include the following:

- Establish primordial isotopic abundances for CHNO; and
- Study martian geological processes that might distinguish biospheric fractionations from geological processes for detection of active metabolism via redox-specific electrodes.