Why Mars Remains a Compelling Target for Planetary Exploration

Prepared on behalf of the Mars Exploration Program Analysis Group (MEPAG) by the MEPAG Executive Committee (Jack Mustard, chair).

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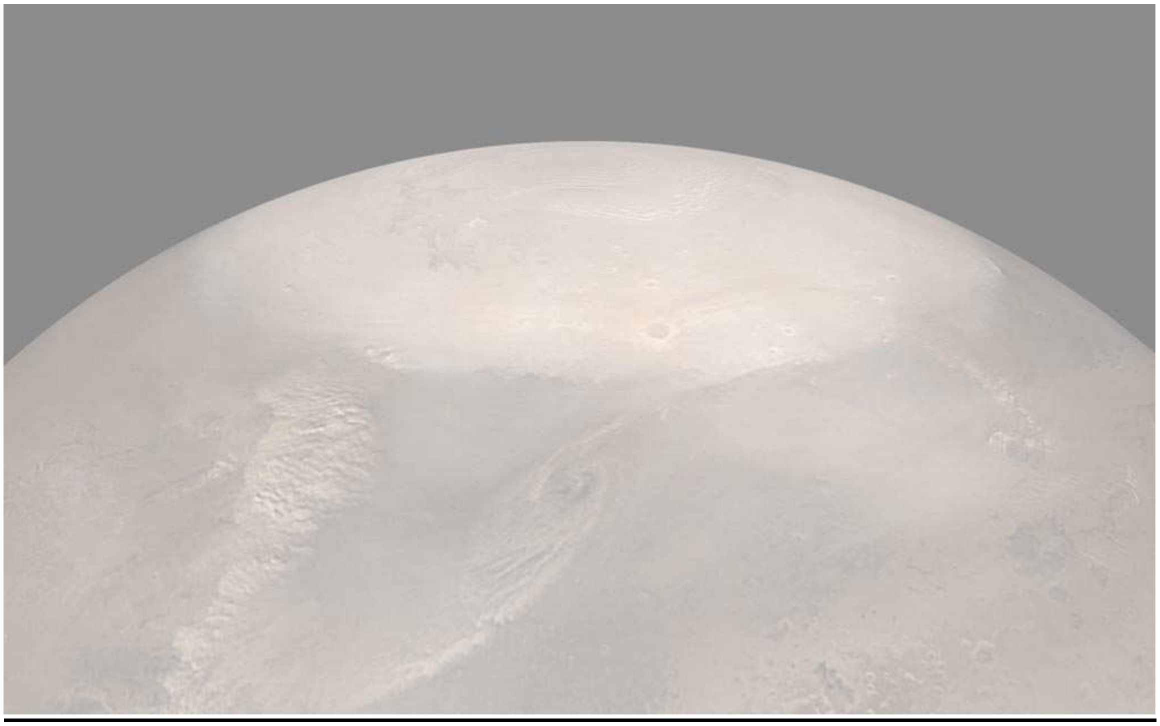

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Introduction[1]

As documented in the most recent Solar System Exploration Decadal Survey (NRC, 2003), Mars has been an extremely compelling exploration target. Because of high international scientific, public, and political interest in Mars since then, NASA has launched three Mars missions (MER, MRO, PHX) and has two more under development (MSL, the selected MAVEN Scout mission); the European Space Agency has launched one (MEX, including Beagle-II); Japan has launched one (Nozomi); and Russia has one under development (Phobos-Grunt). All of the above except Beagle-II and Nozomi returned data. One purpose for the Decadal Survey is to take stock of progress and to re-evaluate the priority of different sectors of the planetary exploration program. In this case, we must ask whether the importance of Mars as an exploration target has changed, given the results to date. Our conclusion is that the exploration of Mars is even more compelling now than it was in 2002.

Historical Context: Mars--A Possible Abode of Life?

For over a century Mars has gripped the imagination of the United States and the world. There are three major components to that fascination:

- The possibility that life has arisen on Mars and may survive there today;
- The chemical and physical record of a planet whose environment has changed dramatically over time;
- Mars, of all the planets, is the most likely destination for human explorers.

The priority of these components has ebbed and flowed, beginning with Percival Lowell's turn-of-the-century perspective of Mars as an older Earth (Lowell, 1896). In the 1960s Mariner fly-bys showed a heavily cratered, moon-like surface beneath a thin atmosphere—in short, an apparently dead, Moon-like world. Mariner 9, the first planetary orbiter, showed how wrong that view was, revealing a surface coursed by great channels and valley networks, a place where dust storms could be global and volcanoes so huge that their base was as large as Arizona.

Our view of Mars changed once again when the Viking landers came up empty in their *in situ* search for evidence of life, particularly organics. Mars again seemed to be a dead world, but one whose climate had clearly been very different in its past. Viking lander exploration ended with the understanding that perhaps we had tried to make too great a leap with its life detection goal. However, there remained much to learn about Mars, some of whose surface had persisted from the earliest periods of the planet's history. This not only harbors the details of Mars' early evolution of chemical, geological and biotic or pre-biotic activity, but also retains a record of planetary evolution of an Earth-like planet unavailable elsewhere in the solar system (Kieffer et al, 1992 and references therein).

A series of small landers and remote sensing orbiters (starting with MPF and MGS) were implemented in a "faster, better, cheaper" era to understand Mars as a planet and to learn about Earth through comparative study. Mars exploration was further energized in 1996 as researchers studying the ALH84001 meteorite re-opened the question of whether there had been life on Mars, and in doing so ignited a debate about whether the microscopic structures and associated minerals in the meteorite were biosignatures (McKay et al., 1996). This debate occurred in the light of terrestrial discoveries showing that life could inhabit extreme environments on Earth; some of which are Mars-like in certain respects. The oxidizing nature of the Martian surface and

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[1] All acronyms used in this document are defined in "Compiled Bibliographic Citations and Acronym Glossary for the Mars-Related White Papers Submitted to the NRC's Planetary Decadal Survey", which may be accessed at http://mepag.jpl.nasa.gov/decadal/index.html.

its significant ultraviolet irradiation were also becoming better understood, perhaps explaining the non-detection of surface organics by Viking. Direct evidence of life might not be everywhere on the surface (the premise of the Viking experiments) but biosignatures could still be present, within the rocks at shallow depth.

Recent Exploration Context: Follow the Water

The Mars Exploration Program (MEP) that emerged (Hubbard et al., 2002) triggered a decade-long program of missions to Mars with four major goals: Life, Climate, Geology/Geophysics, and Preparation for Human Exploration. An organizing theme for the Program was water: where is it now, where had it been and for how long? Essential to life as we know it, water was also a major factor in determining the climate and shaping the surface, and it could be a resource for future human missions to the planet.

From Viking and from the meteoritic analysis we learned that detecting signs of life would be difficult. We recognized that it would first be necessary to understand the environments of Mars, ancient and modern, both morphologic and compositional, to find the habitable places; i.e., those locations that had at least the potential for biochemical processes and for preservation of their biosignatures. As described by NASA (1995), the first objective was to establish the presence, nature and activity of water on Mars in the context of its climatic and geologic history. The logical long-term path for the MEP was therefore summarized with “seek, in situ, and sample” (Hubbard et al., 2002).

These challenging objectives required more capable and costly missions. Increased value of the missions lowered the tolerance for possible loss, and achieving that risk posture further increased the mission costs. The establishment of a Mars Exploration Program in the last decade limited these costs and reduced the science risks by interleaving orbiters and landers of increasing sophistication: Mars Odyssey, two Mars Exploration Rovers, Mars Reconnaissance Orbiter, and the Mars Scout lander Phoenix, joined by the extended operations of Mars Global Surveyor and the arrival of the ESA Mars Express orbiter.

The orbiters provided global and regional context and identified sites of great scientific potential for landed discovery. Landers and rovers followed up on these with detailed *in situ* investigations that verified in part what was seen from orbit, but also revealed stunning chemical, mineralogic, and morphologic properties not observed or anticipated from orbit. At the same time, the orbiters also provided essential mission support by certifying site safety, providing near-real time coverage of critical events, and by supporting surface operations with remote monitoring and telecommunications relay (Edwards et al. 2009). Orbiter dual use is a major factor in controlling cost and reducing risk for the landed craft.

The Mars Exploration Program has made a number of outstanding discoveries over this last decade, a partial list of which follows. It is clearly impossible in a document of this length to list all of the scientific contributors, so we cite some of the key papers and some recent summaries, many of which have comprehensive reference lists.

General

- Based on orbital data from several spacecraft by multiple teams of researchers, planet-wide analyses of comparative geomorphology, surface composition, and relative geologic age (using crater counting methodology) have revealed a planet with a complex geologic record that appears to span most of the history of the planet, and that formed in response to processes that include volcanism/plutonism, weathering/erosion, sedimentation, glaciation, polar ice cap processes, fluid/rock interactions, tectonism, and others. Example references include Christensen et al. (2003), Neukum et al. (2004); Hahn et al. (2007), Tanaka et al. (2005), Frey (2008), and many of the references listed below.

Ancient Mars

- On ancient Mars, water was persistent in shallow surface bodies, lakes, connected networks, and as groundwater near the surface, and Mars therefore likely had a very different climate than it does today (Malin et al. 2003; Hynek and Phillips, 2003; Howard et al. 2005; Irwin et al. 2005; Squyres and Knoll, 2005; Baker, 2006; Jolliff et al., 2006; Knoll and Grotzinger, 2006; Irwin et al. 2008; Squyres et al. 2009, Murchie et al. 2009).
- A diverse suite of minerals, including hydrated sulfates, phyllosilicates, and silica, produced by the action of water on martian crustal rocks has been identified both from orbit and from the martian surface (Poulet et al., 2005, 2009; Squyres et al., 2006a; Arvidson et al., 2008; Morris et al., 2008; Mustard et al., 2008; Squyres et al., 2008; Ehlmann et al. 2008). The character and concentration of at least some of these minerals systematically change on a global scale over geologic time (Bibring, 2006).
- The detailed processes of rock formation and weathering, and the influence of these two processes on mineralogy and morphology/texture has been established at two martian sites of very different geological character (e.g., Grotzinger et al., 2005; McLennan et al., 2005; Squyres and Knoll, 2005; Squyres et al., 2006b; Squyres et al., 2007).
- Remnant magnetism in the ancient crust shows that there was a powerful global magnetic field that shut down early in Mars history, exposing the atmosphere to increased erosion by the solar wind (Connerny et al, 2001; Lillis et al., 2008).
- Determination of the planetary figure and gravity fields (Neumann et al, 2004) provide key information on the distribution of mass and the degree of isostatic equilibrium.

Geologically Young Mars

- Layering in the polar caps and in sedimentary rock in many places, often with remarkably repetitive sequences of layer thicknesses, indicate cyclical processes (e.g. Laskar et al. 2002; Milkovich and Head, 2005; Lewis et al. 2008).
- The north and south polar caps are different in many ways: the north appears younger and has no remnant summertime layer of CO_2. Layer thicknesses for the north have typical variations consistent with computed changes in the planet's obliquity and orbital eccentricity on time scales of several hundred thousand to a few million years (e.g., Phillips et al. 2008).
- An array of glacial and periglacial landforms, including debris covered shallow ice-deposits in mid-latitudes, pointing to massive transport of volatiles, especially water, from the polar reservoirs to lower latitudes, presumably in response to the cyclical changes of polar insolation (Head et al., 2003; Head et al. 2005; Holt et al. 2008; Plaut et al. 2009).

Modern Mars

- Ground ice extends over most of the high latitudes in the top meter of surface material. Its depth (therefore volume) is not known, but a subsurface cryosphere may today hold a significant fraction of ancient liquid water (Boynton et al. 2002; Feldman, et al. 2004; Smith et al. 2009).
- Surface change: Impact craters continue to be identified, helping to calibrate the crater-dating algorithms and providing insight into the material beneath the dust-covered surface. New gullies have been observed; whether dry avalanches or water-aided movement, they indicate a landscape that continues to change even today (Malin and Edgett, 2000; Malin et al, 2006; McEwen et al., 2007).

- A multi-year record of the seasonal cycles of water, CO_2 and dust, including spectacular, episodic hemispheric and global dust events, has revealed processes which operate over much longer time scales (Smith, 2003; 2008). Actively precipitating water ice clouds have now been observed (Whiteway et al., 2009).
- Earth-based observations, building on orbital indications, have detected methane in the atmosphere of Mars (Mumma et al., 2009). Its very presence suggests an active subsurface source. Reported variations in space and time, still controversial, are inconsistent with our present understanding of methane sources and sinks. The all-important provenance of the methane, whether geochemical or biochemical, remains to be determined.

Reasons why Mars remains a compelling exploration target

The processes that have shaped Mars clearly define an Earth-like planet. Like the Earth, Mars has a defined planetary evolution. Its earliest era, the Noachian, was strongly shaped by intense bombardment and gradational processes that sculpted the surface. Fluvial processes integrated and connected to form lakes, leaving finely-layered lacustrine deposits. The middle period of Mars history, the Hesperian, experienced extensive plains volcanism and declining activity of surface water. However, this was the era in which massive eruptions of subsurface water flowed to the northern plains and sculpted the huge channel formations. In the latest era, the Amazonian, volcanism has continued to modify parts of the surface and fluvial activity has persisted episodically in the guise of gullies. But the dominant processes of surface modification have been glacial, periglacial, and polar. Thus Mars has a long and dynamic history of long-lived interior processes that have left a record of volcanic deposits, a changing climate that has shaped and sculpted the surface, and an evolving relationship to water.

A new result that is the subject of intense investigation is that Mars also has a long and diverse history of aqueous mineral formation. The composition of the minerals in the deposits has changed with time, with phyllosilicate minerals predominating during the Noachan, and sulfate minerals during the Hesperian. Few distinctive hydrous mineral deposits are observed in deposits of Amazonian age (Mustard et al., 2008). Some have argued that the particular assemblages of minerals from these two eras signal a transition from an era of abundant water and neutral pH to an era of rapidly declining water activity and very low pH. This new perspective of aqueous mineralogy leads to the hypothesis that Mars underwent a radical reorganization of its planetary systems that has far-reaching implications for habitability.

The success of the MEP over the past decade has expanded our knowledge and focused the science imperative of Mars to tackle new important directions. The current MEPAG Goals Document (MEPAG, 2009) reflects this scientific progress that has been made by past and current missions and the analysis programs. Its listed investigations indicate the pathways needed to respond and move towards the next imperatives. In the following sections, we distill from that comprehensive list those goal areas that have the highest priority for the next decade of Mars, and planetary, exploration.

1. Mars offers critical clues about the early evolution of the terrestrial planets, including our own Earth

The Earth formed (along with the rest of the Solar System) at about 4.5 Ga (billion years ago), but Earth's record in the form of a preserved geologic record extends back in time only to about 3.8 Ga. There are no rocks that reflect the character of the Earth's surface during its earliest period. Studying Earth alone cannot provide direct evidence about the nature of the rock-forming processes, the role of large-scale tectonics, the importance for Earth of the early bombardment and impact history, and the character and significance of processes like water/rock interaction, erosion, sedimentation, volcanism/plutonism, and metamorphism. Since Earth's rocks from 3.5-3.8 Ga are all highly deformed, high-grade metamorphic rocks, most of their original information has been lost. Some detrital zircons from within high-grade gneisses have ages >4 Ga, but their original lithologic context no longer exists. Thus, for the first billion years or so of Earth's history, our ability to read the geologic record is either fragmentary or non-existent.

In contrast, Mars has extensive and spectacular outcrops that represent the same time interval where on Earth the earliest crust formed, plate tectonics began, and life emerged. The exact timing of martian rock-forming events has uncertainty, as it is interpreted based on a model of crater flux as a function of time, but the geology of Mars can be organized into three broad eras, the Noachian (oldest), the Hesperian (middle), and the Amazonian (youngest). The missing time interval on Earth is approximately represented on Mars by the Noachian and the oldest part of the Hesperian.

On Mars, this first billion years was a time of widespread igneous activity, hydrothermal alteration, impact-related cratering processes, erosion, and the formation of a sedimentary record. A relative time stratigraphic context has been established using the methods of photogeology (e.g., Tanaka, 1986). On Earth, the primary rock-destroying process is plate tectonics; because this process did not take place on Mars, there is a spectacular array of well-preserved ancient geologic features. The earliest crust on Mars consists of impact breccias, volcanic and plutonic rocks as well as compelling evidence of fluvial erosion, lacustrine deposits and pervasive weathering. Collectively these indicate at least episodic precipitation and warmer surface conditions occurred during the Noachian than during the rest of the planet's history.

The earliest record of the planetary evolution of Mars is preserved and extraordinarily well exposed. There are windows into the deep crust that provide access to some of the earliest rocks on Mars. Additionally, we can pinpoint specific periods in Mars evolution where its systems underwent major reorganizations. Dozens of unique environments exist where aqueous processes left a record of change, and many of these watery environments varied in their character (e.g., acidity) and agent (groundwater, shallow water, perhaps rainfall). But which of these potentially habitable environments is the most promising for the preservation of diagnostic information and signatures? And which provides access to the suite of materials needed to understand not just potential biochemistry but geochemical processes, as well?

Possible exploration approach (see MEPAG, 2009): Using orbital and landed assets to characterize these environments is an imperative. In addition, the greatest scientific progress possible in the next decades would require returning well-chosen samples from this physical record of the first billion years of a planet's solid existence.

2. Mars provides a means to approach, and possibly answer, questions about the origin and evolution of life

When and how life began on Earth is not yet known. It has been suggested that there is evidence for early life on Earth in rocks as old as 3.8 Ga (Mojzsis et al., 1996), but that part of the geologic record is both fragmentary and highly metamorphosed. A substantial fraction of the scientific community accepts the evidence that life had taken hold on Earth by 3.4 Ga (e.g. observations from the Pilbara Block), and many more accept this conclusion for different kinds of features in rocks as young as about 3.0 Ga in many places (South Africa, Australia, North

America). The general processes by which the inventory of the basic building blocks of life was assembled, how those components were reorganized by the process of pre-biotic chemistry, and how replicating life forms originated and evolved all took place during the critical time period before 3.5 Ga, for which Earth's record is extremely poorly preserved.

Mars has a number of characteristics that make it an exploration imperative for the origins of life. It is a planetary body that today contains the essential ingredients to support and sustain life (e.g. the discoveries of Hecht et al., 2009), and the geologic record is awash in promising ancient habitable environments (e.g. Knoll and Grotzinger, 2006). Clearly, there is potential that life developed on early Mars and that, if it did, there ought to be biosignatures preserved in the ancient rock record.

Furthermore, the detection of non-equilibrium gases (e.g., methane) indicates that there are dynamic processes going on in the Martian subsurface even today that could reflect biological, as well as geochemical, activity. Both biotic and abiotic mechanisms for the origin of the detected methane are consistent with venting from present-day subsurface reservoirs of liquid water. If the methane is abiotic, then a likely source (serpentinization) produces hydrogen, a source of energy and reducing power for microbial life as we know it. If the methane is biotic in origin, then those environments are or were recently inhabited.

Possible exploration approach (see MEPAG, 2009): These discoveries point to a potential two-pronged response for the near future: First, for ancient Mars, a) select and explore *in situ* sites in the ancient crustal areas with high potential for habitability and organic preservation, and b) return samples selected for their astrobiological, as well as geochemical, potential. Second, determine the inventory of atmospheric trace gases, their isotopes, higher-order hydrocarbons, and those key gases which are radiatively or photochemically important.

3. Mars offers a unique opportunity to investigate short- and long-term climate change

Mars has a dynamic atmosphere that has evolved significantly with time. Furthermore, Mars shows clear evidence for periodic climate change. Layering at high and low latitudes, non-polar subsurface ice deposits, and calculation of the large excursions in inclination of the planet's rotation axis, eccentricity and phasing of its orbit all point to large changes in polar sunlight driving major redistributions of water over the planet in cyclic episodes analogous to the Earth's ice ages. As for Earth, these effects have occurred in relatively recent geologic times. Major questions remain about how layers are emplaced, and the time scales of the processes that do so. Answers to these questions depend on an understanding of modern atmospheric transport processes and polar energy balance, as well as refined characterization of layered ice deposits on the planet.

The longer-term variation and the possibility of a geologically rapid change in atmospheric mass and composition relatively early in Mars history demand a closer look. Evidence that the global magnetic field shut down sometime in this period (a time of apparent change in aqueous mineral formation as well) suggests a connection to enhanced atmospheric escape and possibly to internal supply. The evidence points to enormous changes in the abundance and activity of water at this time. Are they related? Was it a rapid transition or a slow decline?

Possible exploration approach (see MEPAG, 2009): The selected MAVEN mission would look at escape processes in the modern atmosphere. A more detailed look at the inventory of atmospheric trace gases and their isotopologues would reveal the possible role of greenhouse gases like sulfur dioxide and thus connections to the volcanic history of Mars. A better understanding of the current internal structure of Mars would provide key modeling constraints.

4. Mars offers a unique opportunity to investigate the internal structure and origin of the terrestrial planets

Understanding the earliest stages of planetary formation, primary differentiation, and subsequent thermal and chemical evolution is one of the central goals of planetary science. The interior structure and state of a planet (including the bulk compositions, sizes and thermodynamic states of its major divisions, core, crust and mantle) contain the best, and, in some cases, the only evidence bearing on these issues. The Earth's evidence, while detailed, is limited by its history of vigorous activity (e.g., plate tectonics, mantle convection, biology itself, tertiary crust formation). As a result, the variations among the four terrestrial planets cannot be reliably explained in terms of primary processes (e.g., accretion, magma ocean formation/fractionation/ solidification, core separation/cooling, planetary convection, core dynamo initiation and shut-down, partial melting and volcanism), as those processes and the conditions under which they operated are poorly constrained. Mars is unique in the accessibility and comparative hospitability of its surface relative to Venus and Mercury. Its level of historical thermal and geological activity, intermediate between the Earth and the Moon, is ideal in attempting both to elucidate the initial conditions and to understand the subsequent processes that have led to the solar system we inhabit today.

Possible exploration approach (see MEPAG, 2009): The key measurements could be provided by a small network of seismic stations. Such a network could also provide platforms for other science, such as meteorological measurements.

Mars is a long-term strategic target for the human exploration program

Mars is a challenging yet attractive long-term strategic target for the human spaceflight program. This goal does not have an intrinsic scientific priority; from the point of view of planetary science, sending humans to Mars would be an exploration means, not an end. However, Mars is an important candidate target for human exploration for reasons other than those related to planetary science. For example, Mars is the only planet in the Solar System that is *realistically* accessible to human exploration. Although we don't have the means to deliver humans to Mars now, the general technical pathway for future access has been mapped out by Drake et al. (2009). To reduce cost and risk for future human exploration, robotic precursor missions would be needed to acquire information concerning potential resources; to perform technology and flight system demonstrations; and to deploy infrastructure to support future human exploration activities.

Mars has been the subject of intense fascination to the public since the time of the ancients. In the modern age, its location in the solar system makes Mars accessible to spacecraft launched from Earth every 26 months, which allows for relatively frequent missions that are coordinated and complementary. Widespread public interest in Mars is continually fueled. This interest is in turn a NASA asset in supporting scientific exploration of the solar system overall, as it fuels an interest in space exploration and discovery, particularly among young people who are the next generation of scientists and engineers.

REFERENCES

The references are compiled in a separate document at the following web site:
http://mepag.jpl.nasa.gov/decadal/index.html.