Mars Exploration Payload Analysis Group

Pathways Science Steering Group Report

"Investigation-Driven Science Pathways for Mars Exploration"

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Executive Summary-1

- Follow discovery-driven approach in which we:
  - Seek to understand the global tectonic, volcanic, hydrologic, and climatic evolution of the planet as the intellectual framework for evaluation of planetary habitability. This includes delineation of the biological potential, including the identification and quantification of geochemical cycles of biological relevance, processes by and extent to which prebiotic compounds were generated, and if and how life developed and evolved.
  - Explore the planet globally, including magnetosphere, atmosphere, surface, and interior, testing key hypotheses and addressing critical questions.
  - Locate and characterize sites, both surface and subsurface, where key evidence for the evolution of the planet and its habitability might be found.
  - Explore in detail sites with high habitat potential, characterize the deposits (e.g., hydrothermal alteration zones or aqueous deposits) using mineralogical, geochemical, and geophysical techniques, search for and characterize biosignatures, and conduct appropriate life detection experiments.
  - Return samples from high priority sites for detailed laboratory analyses focused on the evolution of the planet, its habitability, and the search for fossil and extant life.

Executive Summary-2

- Discovery-driven pathways using this top-down approach should focus on continuing global orbital and landed observations to understand the planet and its evolution, together with investigations focused on ancient lacustrine or marine deposits, polar ices, subsurface ice, sediments, hydrothermal deposits, and characterization of the global groundwater system.
- Be discovery-driven, but recognize that long lead times for technology development and high costs of missions require careful and long-term planning.
  - *A judicious mix of orbital and surface-based measurements, combined with analyses of returned samples, will be needed to meet science objectives.*
  - *Perform innovative and novel observations at each orbital and landed opportunity, measurements that are likely to revolutionize our understanding of the evolution of the planet and its habitability.*
- Recognize that many important science objectives can and/or must be met using *in-situ* observations, including those that focus on:
  - *Ground truth for orbital measurements.*
  - *Initial site characterization to determine mineralogy, elemental abundances, isotopic composition, redox potential, detection of biosignatures, and life detection.*
  - *Characterization of the interior (e.g., heat flow, seismicity, water and ice distribution), the dynamics of the environment (e.g., atmosphere-surface dynamics), and/or analyses of labile samples (e.g., with oxidants).*
- Recognize that it will be impossible to duplicate, with *in-situ* observations, many of the sophisticated and evolving analytical measurements that can and should be done in laboratory settings.
  - *Samples must be returned to Earth for laboratory analyses AT THE EARLIEST POSSIBLE DATE to achieve a full understanding of the evolution of Mars, its habitability, and whether or not life started and evolved.*
  - *Analyses of returned samples will facilitate discovery-driven science in that results will strongly influence future science investigations to be conducted on mars.*

Why Explore Mars?

- Analysis of Viking, Pathfinder, Mars Global Surveyor, Odyssey, and Mars meteorite data demonstrates that the geologic record of Mars is complex, extends over a long period of time, and contains a rich record of the interplay among tectonic, volcanic, hydrological, and climatic processes.
- It is likely that at various times and places conditions existed that would have been conducive to generation of prebiotic compounds and perhaps life. If life developed and evolved under clement conditions, it may still exist today in local, protected niches.
- Mars may preserve evidence for prebiotic and/or early biotic processes comparable to what transpired on early Earth, evidence that was long ago destroyed on our own planet.
- Thus, exploring Mars will tell us how a neighboring, Earth-like planet evolved, whether or not conditions for generation of prebiotic and biotic systems existed, and the evidence preserved. These issues are at the core of planetary habitability.
- Environments and associated deposits with high potential for development and preservation of prebiotic compounds and biosignatures include:
  - *Ancient lakes and associated sedimentary deposits*
  - *Modern and ancient ground water systems and associated mineralization zones*
  - *Modern and ancient hydrothermal systems and associated mineralization zones*
  - *Polar ice and associated sedimentary deposits*
- A global understanding of the spatial and temporal patterns and mechanisms of interplay among tectonic, volcanic, hydrological, and climatic processes is necessary to understand the context for and locations of targets with high potential for: (a) habitat development and preservation of evidence of prebiotic compounds and biosignatures and (b) the presence of extant life.

Note: For reference, biosignatures are defined to be morphologic, mineralogical, chemical, or isotopic measurements indicative of fossil or extant life. Life detection is defined to be measurements/experiments focused on detection of extant or fossil life.

What We Think We Know About Mars

- Geologic History From Old to Young
  - Formation of crust that recorded early period of heavy impact bombardment.
  - Mega-impact or global tectonic event formed crustal dichotomy.
  - Early global magnetic field generated and then stopped.
  - Tharsis volcano-tectonic complex emplaced with resulting global deformation.
  - Valley networks formed by running water, perhaps with lakes and seas.
  - Thicker atmosphere removed by impact erosion, solar wind stripping, or formation of carbonate rocks.
  - Crust became frozen in most places up to to a kilometer or more in depth.
  - Break-out channels formed that are indicative of massive release of local to regional-scale ground water reservoirs.
  - Deposition and removal of layered deposits continued throughout geologic time, modulated by volcanic and climatic processes.
  - Episodic release of ground water continued to present.
  - Quasi-periodic oscillations in orbital obliquity, eccentricity, combined with spin axis precession, caused continuing shifts in climatic conditions, with detailed record left in polar layered deposits of sediment and ices.
  - Throughout geologic time organic material has been added to the surface via meteoritic infall.

Outstanding Questions About Mars

- Questions posed are directly related to understanding the global tectonic, volcanic, hydrologic, and climatic evolution of Mars as an intellectual framework for evaluation of planetary habitability. This framework includes understanding the nature and history of geochemical cycles of biological relevance, and development of prebiotic compounds and life, all within an understanding of the global evolution of the planet.
  - What is the origin of the crust and the source of biogeochemically important species, i.e., compounds containing carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur, known as "CHNOPS" and related species such as Fe and Mn?
  - What role has the addition of organic materials via meteoritic infall had on the development of life?
  - What is the nature and history of the global magnetic field and implications for surface habitability?
  - What is the thermal history of Mars (including Tharsis)?
  - What has been the nature of the interplay and timing among tectonic, volcanic, hydrological, and climatic processes and how have these processes shaped the composition and structure of the crust and surface and availability of CHNOPS-bearing compounds?
  - What has been the stability of water at the surface over the history of Mars?
  - How and when did the climate evolve? Was there a secular decline in atmospheric mass? Were there significant episodic processes? What were the mechanisms for atmospheric removal? What was the role of volatile release by volcanism in modulating the climate, particularly Tharsis-related degassing?
  - What have been the reservoirs for water/ice in space and time? How has water been exchanged among various reservoirs and how have the reservoirs and fluxes changed through time? Did Mars support a full hydrologic system with rainfall, runoff, and surface water bodies such as lakes and seas? How extensive were hydrothermal systems and where were they?
  - What cycles governed the distribution and bio-availability of CHNOPS-compounds and related species? Where are the reservoirs of these materials?
  - What combination of tectonic, volcanic, hydrologic, and climatic conditions existed or exist for generation and preservation of prebiotic compounds? Were these compounds generated and preserved?
  - Did life develop and evolve on Mars and in what habitats? Is the evidence preserved and can it be understood within a context of global interactions of tectonic, volcanic, hydrologic, and climatic processes and cycles?
  - If life developed during earlier, more clement conditions, and became widespread, could it still exist today in the subsurface, or in localized near-surface niches?
  - How have quasi-periodic changes in orbital parameters modulated climate and habitability and what is the evidence?

Mars Exploration Program Through 2007 Timeframe

- MGS and Odyssey will provide global maps of morphology, topography, gravity, magnetic field, mineralogy, composition, and near-surface water/ice content. Odyssey will map seasonal variations in near-surface carbon dioxide ice.
- 2003 Mars Exploration Rovers will explore two sites of high potential for determining past water-surface-subsurface interactions, ideally landing on what have been hypothesized to be hydrothermal (e.g., hematite and substrate exposures in Terra Meridiani) and lacustrine (e.g., layered units in Gusev Crater) deposits.
- 2003 Beagle 2 Lander will explore shallow subsurface in Isidis Planitia and provide elemental, mineralogical, and isotopic data for soils.
- 2003 Mars Express Orbiter and 2005 Mars Reconnaissance Orbiter (MRO) will provide:
  - *Detailed mineralogical and morphologic data for landforms and deposits that are key to understanding the nature and history of postulated fluvial, lacustrine, marine, and hydrothermal systems and associated habitat and preservation potentials.*
  - *Depth to water table, if a well-defined water table exists, and to confined aquifers.*
  - *Distribution of subsurface ice.*
  - *Data to understand the current water-carbon dioxide-dust cycles and dynamics.*
- 2007 CNES Netlander will focus on network science to determine atmospheric dynamics and seismicity of interior. CNES Orbiter will map atmospheric dynamics, focusing on water-carbon-dioxide-dust cycles and dynamics.
- 2007 Scout will consist of high priority, focused science investigation(s).

2009 Mars Smart Lander: An Evolving Mission Concept

- Will feature precision landing of vehicle and payload on target with high habitat and preservation potential, e.g., layered sedimentary deposits indicative of lacustrine or marine systems in which rapid accumulation and lithification preserved information about conditions that existed during formation of the deposits.
- Will focus on testing hypotheses related to the origin and evolution of the site and its deposits, including geologic setting, mineralogy, composition, redox potential and presence of biosignatures, including organic compounds, isotopic signatures, and textural indicators (e.g., from high resolution microscopy) for surface and perhaps shallow core samples.
- May feature nuclear-powered “Explorer Rover” capable of global access to the surface, with a mission lifetime of approximately 1000 sols.
- Judicious feed-forward to Mars Sample Return, including precision landing of large payload and site/soil/rock characterizations.

Building Blocks for Understanding Planetary Habitability

- Follow a discovery-driven approach that focuses on understanding planetary habitability (i.e., biological potential) in the context of the global tectonic, volcanic, hydrologic, and climatic evolution of the planet, including the nature and history of geochemical cycles of biological relevance, detection of biosignatures and the search for extant life.
  - Explore the planet globally, including magnetosphere, atmosphere, surface, and interior, and test critical hypotheses and address major questions related to the evolution of the planet and its biological potential.
  - Locate sites with high habitability potential that are likely to preserve evidence for biosignatures and life.
  - Explore and characterize these sites, including mineralogical, geochemical, and geophysical measurements, evidence for biosignatures, and life.
  - Return samples from one or more of these sites for detailed and evolving analyses focused on the evolution of the planet, its habitability, and the search for biosignatures and life.

Building Blocks for Discovery-Driven Science-2

- The discovery-driven approach to understanding the evolution of Mars as the intellectual framework for habitability and life:
  - Includes continued orbital and landed investigations and analyses of returned samples as fundamental elements.
  - Recognizes that long lead times for technology development and high costs of missions require careful and long-term planning.
  - Performs innovative and novel observations at each orbital and landed opportunity, measurements that are likely to revolutionize our understanding of the evolution of the planet, its habitability, and evidence for fossil and extant life.

Building Blocks for Discovery-Driven Science-3

- Recognize that many important science objectives can and/or must be met using *in-situ* observations, including those that focus on:
  - *Ground truth for orbital measurements.*
  - *Initial site characterization to determine mineralogy, elemental abundances, isotopic composition, redox potential, detection of biosignatures, and life.*
  - *Characterization of the interior (e.g., heat flow, seismicity, water and ice distribution), the dynamics of the environment (e.g., atmosphere-surface dynamics), and analyses of labile samples (e.g., with oxidants).*
- Recognize that it will be impossible to duplicate, with *in-situ* observations, many of the sophisticated and evolving analytical measurements that can and should be done in laboratory settings.
  - *Samples must be returned to Earth for laboratory analyses AT THE EARLIEST POSSIBLE DATE to achieve a full understanding of the evolution of Mars, its habitability, and whether or not life started and evolved.*
  - *Analyses of returned samples will facilitate discovery-driven science in that results will strongly influence future science investigations to be conducted on Mars.*

Examples of Discovery-Driven Pathways

- Four *example* pathways are provided that illustrate how discoveries can influence the approach to meeting science objectives.
- Decision to go along a particular path will be driven by the perceived importance and excitement of discoveries as expressed to the Mars Exploration Program by the science community, and by available resources and other programmatic constraints.
- The pathways make assumptions as to what will be discovered using Odyssey, MER, and MRO and other data and thus what 2009 MSL and future investigations might focus on.
  - *For 2009 MSL use results from Odyssey, MER, Mars Express to help select landing site with high potential for generation and preservation of evidence related to habitability and life.*
  - *Sample return and associated laboratory analyses are critical elements for each example.*
- Examples include:
  - *Continued global orbital and landed exploration designed to better understand the global evolution of the planet and implications for habitability and life.*
  - *Exploration and analysis of surface and shallow subsurface polar ices and sediments as a habitability and life focus.*
  - *Exploration and analysis of subsurface ice, water, and mineralization zones as a habitability and life focus.*
  - *Exploration and analysis of ancient lacustrine and/or hydrothermal deposits as a habitability and life focus.*

Example Pathway: Understand Habitability Through Space and Time

- WHAT WOULD LEAD US TO THIS PATHWAY?
  - On-going orbital reconnaissance of Mars by MGS and Odyssey has resulted in the the emergence of exciting, yet contradictory hypotheses related to habitability and life. Some of the key issues include: If early warm, wet conditions were supported by carbon dioxide greenhouse, where are carbonate deposits? If shallow seas existed, where is the evidence for salts and other weathering products? Were the best habitats at the surface during early times when the magnetic field was active (and shielded the planet from radiation) and seas might have existed, or were the best locations always in the subsurface?
  - Orbital reconnaissance has also identified a large number of prime targets for future surface exploration that will allow addressing these types of questions – each of which may reveal important aspects of the evolution of the planet and its habitability. These targets are localized, non-contiguous, and widely distributed about the planet.
  - We will only sample four sites in current program (two MERs, Beagle 2, 2009 MSL).
  - We need to close the "lander gap" and continue orbital observations to understand the global evolution of Mars, its habitability, and implications for the origin and evolution of life.
- HOW TO RESPOND?
  - A program that includes relatively inexpensive, multiple, focused orbital and *in-situ* studies at a large number of sites to reduce the time required to follow up on new discoveries by ongoing and future Mars missions.
  - A series of "Mars Diversity Missions" that "follows the water" (which apparently has been in many places on Mars in many forms), characterizes geochemical cycles of biological relevance and searches for biosignatures and life.
  - Focused *in-situ* studies at a variety of sites would provide an informed context for the planning of an "eventual" sample return mission.

Example Pathway: Focus on Polar Climatic and Habitat Records

- WHAT WOULD LEAD US TO THIS PATHWAY?
  - Odyssey NS and HEND observations show abundance of near-surface ice at high latitudes. Models developed demonstrate that ice can melt during the polar summer or during high obliquity periods. Thin layers of water are predicted, thus enhancing the habitability potential of the deposits.
  - MRO CRISM/HIRISE observations pinpoint locations in which erosion has exposed layered section of water and carbon dioxide ice and sediment.
- HOW TO RESPOND?
  - Use orbital observations to select polar landing sites that would maximize access to ice and sedimentary stratigraphy.
  - Use 2009 MSL rover to explore polar site, test hypotheses related to origin of ice and sedimentary deposits, infer how the deposits fit into global scale tectonic, volcanic, hydrologic, and climatic contexts, and search for biosignatures and life.
  - Explore new sites with combination of Scout and Smart Lander type missions, focusing on new, innovative measurement approaches for understanding polar processes and the evolution of the planet and its habitat, biosignatures, and life.
  - Continue to obtain orbital measurements, e.g., detailed measurements of remanent magnetic field, to understand global evolution of Mars and its habitability.
  - Return samples from key site as soon as feasible for detailed analyses, perhaps from the geologic units explored and characterized during the 2009 MSL Mission or subsequent landed missions, since these sites would be characterized in great detail, thereby facilitating sample selection.

Example Pathway: Focus on Subsurface Exploration

- WHAT WOULD LEAD US TO THIS PATHWAY?
  - Detection of anomalously warm surface temperatures by Odyssey THEMIS or evidence of liquid water or ice deposits at shallow depth by Mars Express MARSIS, MRO SHARAD, or Odyssey NS.
  - Orbital and/or landed *in-situ* observations that demonstrate the need to access subsurface materials to get beneath a globally deep oxidation zone (requiring deeper access in the search for organics).
  - Orbital and/or landed *in-situ* observations that demonstrate significant aqueous alteration associated with hydrothermal and groundwater circulation systems. Surface access limited.
- HOW TO RESPOND?
  - Use 2009 MSL to drill into the shallow subsurface and analyze cored material to determine composition, mineralogy, presence of biosignatures, and perhaps life detection. Would provide important ground truth for orbital investigations and could assist in understanding the geologic, hydrologic, and climatic history of Mars.
  - Further subsurface characterization by orbiter and surface-based geophysical investigations, e.g., orbital 3-D radar interferometery, ground-based geophysical networks, rovers equipped with GPR, active and passive low frequency EM experiments, and active and passive seismic experiments.
  - Targeted drilling investigations (at multiple locations and to greater depths than achieved by 2009 MSL). Sites suggestive of past or present near-surface water investigated using a combination of Scout and MSL type missions. Down-hole investigations would include heat flow, resistivity logging, other types of geophysical measurements, and detailed *in-situ* core analyses including the search for biosignatures and life.
  - Return surface and subsurface samples from key site as soon as feasible for detailed analyses, perhaps from the geologic units explored and characterized during the 2009 MSL Mission or subsequent landed missions, since these sites would be characterized in great detail, thereby facilitating sample selection.

Example Pathway: Focus on Ancient Geologic and Habitat Records

- WHAT WOULD LEAD US TO THIS PATHWAY?
  - MGS/Odyssey/MRO observations and results from Mars Exploration Rovers and Beagle 2 indicate with confidence that there are layered sedimentary deposits of lacustrine or marine origin and/or locations where hydrothermal alteration deposits are well preserved. These are deemed to be likely candidates for preservation of evidence related to habitability, including "CHNOPS" bearing compounds, and become high priority targets for searching for evidence for prebiotic compounds, biosignatures, and life.
- HOW TO RESPOND?
  - Use 2009 MSL rover to explore key site, test hypotheses related to origin of deposits, infer how the deposits fit into global scale tectonic, volcanic, hydrologic, climatic and habitat contexts, search for biosignatures.
  - Explore new sites of high scientific potential with combination of Scout and Smart Lander type missions, focusing on new, innovative measurement approaches for understanding the evolution of the planet, habitats, biosignatures, and life.
  - Continue to obtain orbital measurements, e.g., detailed measurements of remanent magnetic field, to understand global evolution of Mars and its habitability.
  - Return samples as soon as feasible from key site for detailed analyses, perhaps from the geologic units explored and characterized during the 2009 MSL Mission or subsequent landed missions, since these sites would be characterized in great detail, thereby facilitating sample selection.

Program Implications-1

- Science missions needed to pursue discovery-driven pathways depend critically on technology developments.
  - Safe and precise landings with global access and long duration surface operations.
  - Access to and preparation of key samples, both surface and subsurface.
  - *In-situ* instrumentation that provides precise, accurate measurements.
- Investment in technology must be integral element of the program.
  - Early identification and funding of technology is essential (5 - 10 yrs is required in some cases from concept to flight).
  - Benefit of pathway planning is the identification of required and enabling technologies.

Program Implications-2

- Technology investments across different pathways have some elements in common
  - Controlled entry, lightweight components, precision landing, and long-lived assets benefit all surface missions.
  - Development of *in-situ* instrumentation and associated sample handling and preparation systems required to analyze rock/soil/ice texture, composition, mineralogy, organic compounds, biosignatures, and life detection critical for all surface missions.
  - Development of affordable planetary protection capabilities to minimize forward contamination critical for collecting, and analyzing samples.
- Some technologies are unique to Sample Return Missions
  - Efficient propulsive ascent from the surface of Mars
  - Rendezvous in Mars orbit between ascent elements and Earth return vehicles
  - Safe, assured containment return of samples to the surface of Earth
  - Returned sample handling technologies once samples received after landing
  - Additionally, many of other technologies discussed herein are beneficial or critical to Sample Return missions

Program Implications-3

- Technologies required for global access address several challenges:
  - Higher elevations in southern hemisphere mandate lightweight systems.
  - Geometric access of all points via direct entry not always feasible (e.g. the poles).
    - Orbital entry and/or aerocapture address this issue.
  - In polar regions, winter loss of visibility of Sun (thermal/power) and Earth (direct communications) drives technical requirements.
  - Long-range, efficient mobility increases access to surface sites of scientific interest.
- ***Long development times for many of enabling capabilities demand an early investment in order to avoid precluding alternate pathways.***
- ***Early and sustained investments thus maximize program responsivity to exciting new discoveries about Mars.***