Planning for the Scientific Exploration of Mars by Humans

By the MEPAG Human Exploration of Mars Science Analysis Group

MEPAG Human Exploration of Mars Science Analysis Group (HEM-SAG)
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EXECUTIVE SUMMARY

Mars will remain an attractive destination for science for decades to come and the pace of discoveries about the workings of the Red Planet could be dramatically accelerated by means of human-based exploration at any time it becomes possible. In the context of a set of three initial human expeditions to Mars at some time beyond the current event horizon (i.e., in ~25 years, meaning 2030s or 2040s), a team of experienced planetary scientists with diverse scientific backgrounds has analyzed scientific priorities and scenarios for such missions, under the overarching precept that scientific discovery is a major aspect of such missions. The Human Exploration of Mars Scientific Analysis Group (HEM-SAG) derived human science reference missions using constraints provided by engineers affiliated with the 2007 Mars Architecture Team (B. Drake et al., NASA JSC) as well as the current scientific priorities for Mars exploration summarized in the 2007 MEPAG Goals and Objectives reference document as well as recent National Academy of Sciences Solar System Decadal Survey recommendations (New Frontiers, NRC, 2003). After initial evaluation of the state of knowledge about Mars today (circa 2007), the HEM-SAG projected this state of knowledge forward to ~2030, under the assumption that a robotic Mars sample return mission must be accomplished prior to Human scientific activities on the martian surface. The HEM-SAG concluded that in any science-driven or science-guided program of human exploration, each of three baselined human missions must visit independent and distinct “exploration sites” for maximal periods of time, as dictated by the realities of flight dynamics and celestial mechanics. Thus, the overarching conclusion of the HEM-SAG is for three human exploration missions to scientifically (i.e, in terms of surface age of materials and scientific problem focus) target different regions for periods of up to 500 days on the surface, enabled by means of moderate-to-long range human mobility (100’s of km) and multi-100m scale subsurface access. Scientific priorities at the time of the first HEM missions (2030s or 2040s) would likely remain similar to those of today, in spite of major progress underway from the current US and International robotic Mars programs (NASA’s MEP, ESA’s science programme). In addition, there are “pass-backs” from what we need to be able to accomplish on Mars for science that could be validated and optimized via human exploration activities on the Moon, including unique aspects of sample acquisition and handling, in situ characterization, deep subsurface access, and long-range surface mobility, potentially with pressurized human roving vehicles. Mars, in the view of the HEM-SAG, represents an ideal target for intensive human-based and enabled surface scientific operations for the next 50 years.

HEM-SAG INTRODUCTION

To prepare for the exploration of Mars by humans, as outlined in the new national Vision for Space Exploration (VSE), the Mars Exploration Program Analysis Group (MEPAG), formed a Human Exploration of Mars Science Analysis Group (HEM-SAG) in March 2007. The goal of HEM-SAG is to develop the scientific goals and objectives for the scientific exploration of Mars by humans. The HEM-SAG is one several parallel NASA humans to Mars scientific, engineering and mission architecture studies going on in 2007 to support NASA's planning for the VSE. The HEM-SAG consists of about 30 Mars scientists representing the disciplines of Mars geology, geophysics, atmospheric/climate science and biology/life science from the U.S., Canada, England, France, Italy and Spain (It was decided very early that the international Mars community should be represented on HEM-SAG). Drs. James B. Garvin (NASA Goddard) and Joel S. Levine (NASA Langley) were appointed co-chairs of HEM-SAG. The HEM-SAG team conducted 20 telecons beginning on March 21, 2007. HEM-SAG convened three face-to-face meetings: 1. May 3-4, 2007, at USRA Headquarters, Columbia, MD, 2. July 8, 2007 at the Pasadena Hilton, and 3. October 23-24, 2007, at USRA Headquarters, Columbia, MD, On May 17, the interim HEM-SAG interim findings were reported to MEPAG management (Drs. Ray Arvidson, past MEPAG Chair and Jack Mustard, MEPAG Chair) and MEP management (Drs. Michael Meyer, MEP, NASA Headquarters and Rich Zurek, MEP, JPL) via telecon.

The scientific goals and objectives for the human exploration of Mars discussed in this report are based on the Mars Scientific Goals, Objectives, and Priorities: 2006, (MEPAG, 2006) (J. Grant, editor, 31 page white paper posted February, 2006, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/index.html.

HEM-SAG Starting Assumptions

1. The first human mission to Mars may be scheduled for launch as early as 2030, and as late as 2040. In this study, only consider the first three human missions to Mars.
2. Assume that the scientific objectives for the first human mission to Mars would be set based on cumulative knowledge and priorities as of about 5 years before launch.
3. Assume that the robotic exploration of Mars would continuously operate from now until the first human mission.
4. Because the timing of the second human mission to Mars relative to the first is subject to large uncertainties, for the purpose of this planning exercise, the HEM-SAG should focus on to develop inputs into the planning the baseline architecture for the first, and possibly subsequent, human missions to the Martian surface.

HEM-SAG Requested Tasks

5. Starting from the current version of the MEPAG (2006), develop an analysis of the probable/possible evolution of our scientific goals and objectives for Mars over the next three decades. The scientific goals and objectives of a future human mission would need to be based on this projection, not on today's list.
    a. Which of MEPAG's current scientific goals, objectives and investigations would have been met, all or in part?
    b. Since the nature of science is that investigations not only answer questions, but almost always also raise new ones, how are the current objectives and investigations likely to evolve into future ones?

6. Develop an analysis of the spectrum of possible scientific objectives that would be appropriate for a future human mission to Mars.
    a. Evaluate the advantage to an implementation involving humans for different kinds of scientific investigations
    b. Analyze the opportunity to take scientific advantage of the engineering aspects of a human mission.
7. Based on the above considerations, develop an analysis of the probable/possible relative priority of the identified candidate scientific objectives.

WHY MARS?

Mars is a unique and complex world. Many of the same processes/mechanisms operate/operated on both Earth and Mars, e.g., early heavy bombardment, impact craters, planetary dipole magnetic field, widespread and extensive volcanism, the presence of liquid water on the surface, geochemical cycles, the condensation of atmospheric gases forming polar caps, etc. Mars, like the Earth, is a terrestrial planet with a very diverse and complex surface features and processes. Like the Earth, Mars is also a possible abode for past and/or present life. The geological record suggests that the atmosphere/climate of Mars has changed significantly over its history. Early Mars may have possessed a denser atmosphere, perhaps with a surface atmospheric pressure in excess of 1000 millibars, the surface pressure of the Earth's atmosphere. A denser atmosphere on Mars would have permitted liquid water on its surface. Present-day Mars has a thin (6 millibars) cold atmosphere, devoid of any surface liquid water. Why has Mars changed so drastically over its history? How and why has the habitability of Mars changed over its history? Is there a message in the history of Mars to better understand the future of the Earth?

WHY HUMANS?

Humans have unique capabilities for performing scientific measurements, observations and sample collecting. Human attributes to exploration include: intelligence, adaptability, agility, dexterity, cognition, patience, problem solving in real-time, in situ analyses - more science in less time!

Humans are unique scientific explorers. Humans could obtain previously unobtainable scientific measurements on the surface of Mars. Humans possess the abilities to adapt to new and unexpected situations in new and strange environments, they can make real-time decisions, have strong recognition abilities and are intelligent. Humans could perform detailed and precise measurements of the surface, subsurface and atmosphere while on the surface of Mars with state-of–the-art scientific equipment and instrumentation brought from Earth. The increased laboratory ability on Mars that humans offer, would allow for dramatically more scientific return within the established sample return limits. The HEM-SAG envisions that the scientific exploration of Mars by humans would be performed as a synergistic partnership between humans and robotic probes, controlled by the human explorers on the surface of Mars. Robotic probes could explore terrains and features not suitable or too risky for human exploration. Under human control, robotic probes could traverse great distances from the human habitat covering distances/terrain too risky for human exploration and return rock and dust samples to the habitat from great distances.

An important element of the HEM-SAG study has been to identity the unique capabilities that humans would bring to the process of exploring Mars. As a result, a common set of human traits emerged that would apply to exploration relating to the MEPAG Goal III science disciplines which include Geology, Geophysics, Atmosphere/Climate, and Biology/Life,. These characteristics include: speed and efficiency to optimize field work; agility and dexterity to go places difficult for robotic access and to exceed currently limited degrees-of-freedom robotic manipulation capabilities; and most importantly the innate intelligence, ingenuity, and adaptability to evaluate real-time and improvise to overcome surprises while ensuring that the correct sampling strategy is in place to acquire the appropriate sample set.

The unique capabilities that humans would provide for each of the MEPAG Goal III science disciplines mentioned above are summarized as follows:

Geology

Intelligent sample selection, real time assessment of site sampling progress and strategy development to optimize science return.

Drilling in environments difficult for core recovery (ice, sediments, other unconsolidated materials) without human involvement.

Rapid assessment of subsurface and sampling/trenching (efficiency factor).

Geophysics

Humans are likely to be far more efficient and skilled than robots in carrying out the careful emplacement of instruments, networks, and site surveys required to meet geophysical investigation goals and objectives. Even if rover-borne instrumentation is deployed tele-robotically, that would require human oversight from the habitat. Some geophysics instrumentation must be deployed and then recovered following measurements (e.g., active seismic systems, or EM sensors). Humans would make this deployment/recovery process more efficient and perhaps even more carefully done, as well as providing instant gratification on the health and performance of the instruments.

Atmosphere/Climate

Human enabled investigations on Mars would benefit atmospheric, polar cap, and ancient climate science objectives in a variety of ways. Human dexterity and efficiency would be important qualities for micrometeorological investigations where activities such as radiosonde preparation and release are not yet automated on Earth due to the dynamic interaction with surface turbulence and winds. Cognitive ability, dexterity and efficiency would be necessary attributes in the search for relevant rock outcrops and samples, providing the ability to identify sources of trace gases for studies of current climate on Mars as well as locating pristine impact glasses containing trapped gasses for the study of ancient Mars climate. These unique human capabilities would be vital to deep drilling and coring activities. Touch and sound would be used to monitor the drill performance and respond rapidly to changing subsurface conditions.

Biology/Life

Earth-based investigations into the purported evidence for life in Martian meteorite ALH84001 have involved a great number of scientists utilizing many sophisticated instruments and techniques but remain controversial. Evidence of life on Mars, both past and present may be quite subtle. The selection of relevant samples and sampling environments would require the unique capabilities of humans (e.g., ingenuity, flexibility, efficiency) to interpret available clues in real time and to strategically execute a plan for investigation of hypotheses in situ. Humans bring to planetary exploration the ability to quickly analyze and assess samples before they degrade locally or on return. Samples should still be returned to Earth because of the advanced analytical capabilities of terrestrial laboratories, but the increased capabilities humans would provide on Mars, and the remarkable advances that have and would continue to be made in lab instrument miniaturization mean more science reaped without the restrictions of sample weight on return and a greater likelihood of satisfying the goals and objectives of the mission.

We believe that the human element is value added to all aspects of the MEPAG Goals and Objectives. Technology development in the decades leading up to a human mission to Mars would determine the best synergistic fit between human and robotic exploration and perhaps technology challenges would be overcome to shift the balance of physical activity toward robotic assignment. However, certain uniquely human attributes could not be duplicated by or relegated to robots or to operations remotely operated by humans on a planet substantially separated in time and space from Earth. Only a human presence in Mars mission surface operations activities could facilitate and achieve the ambitious scientific goals and objectives of MEPAG.

SOME HEM-SAG GENERAL CONCLUSIONS

For the first three human missions: three different sites or the same site?

Three independent sites.

For the first three human missions should they be: "short stay (~30 days)" or "long Stay (~500 days)"?

Three long-stay (~500 days) missions to maximize scientific return.

How much surface mobility, in terms of radial distance from landing site, would be required to perform the required science?

Human mobility (horizontal)/pressurized human rover >200 km radial (Perhaps >500 km).

What would be the subsurface access requirements?

Vertical subsurface access (drilling) ~300 m at one site for access to subsurface liquid water zones, if available; less (5-50 m) at multiple sites on traverses. Selective recoverable coring, e.g., polar climate coring to depth of 300 m.

How would we implement a search for extant life vs. a search for fossil life? (Assessing the human of human explorers on the search for extant life)

Very carefully. The search for extant biology must be an important scientific goal/objective of human exploration. Humans have a great deal of experience in carrying out aseptic sampling of exteme environments on Earth to carry forward in this endeavor

Human in-situ analyses on Mars vs. returning samples to Earth for analyses (Mass of instrumentation/equipment transported from Earth to Mars for in situ analyses on Mars versus amount of sample mass to be returned to Earth)

Human habitat/work station: In situ sample analysis and cataloging: Analyses that could not be performed on Earth, e.g., tests for extant life.

Samples would include rocks, drill cores, surface/atmospheric dust, ice, atmospheric gas.

Sample conditioning and preservation would be essential.

Human habitat LAB instruments for multiple objectives: Geology, Atmosphere/Climate and Biology/Life.

Emplacement of network stations for Geophysics, Atmosphere/Climate and even Biology/Life would be essential beyond initial landing site (200-400 km radial from landing site) to be operated during and after humans return to Earth.

How much sample mass should be returned to Earth?

Mass of samples returned to Earth >250 kg.

GEOLOGY: HUMAN EXPLORATION GOALS AND OBJECTIVES

What Would Be the Key Scientific Goals and Objectives of Human Exploration of Mars In Geology and What Would be the Sample Human Science Reference Missions (HSRM) In Geology?

While current and future robotic Mars missions would provide insight regarding the geology of Mars, HEM-SAG concluded that the fundamental top-level questions with regard to Mars would likely remain broadly the same over the next 20 years. Among those questions are:

1. What is the volcanic history of the planet, and is Mars volcanically active today?
2. What was the nature and evolution of the Martian magnetic field?
3. What is the climate history of Mars?
4. What is the hydrologic history of Mars?
5. Is Mars hydrologically active at the present time?

These questions have wide-ranging implications with regard to the evolution of the Solar System, the nature and evolution of Earth's surface and climate, and the feasibility and likelihood of biology on another planetary body. The complex history of the Mars, and the evolution of Mars from the potentially "warm and wet" periods of its early Noachian history to the later "cold and dry" period of the Amazonian, strongly suggest that an exploration strategy that addresses the characteristics and processes of the three major periods would be required (Figure 1).

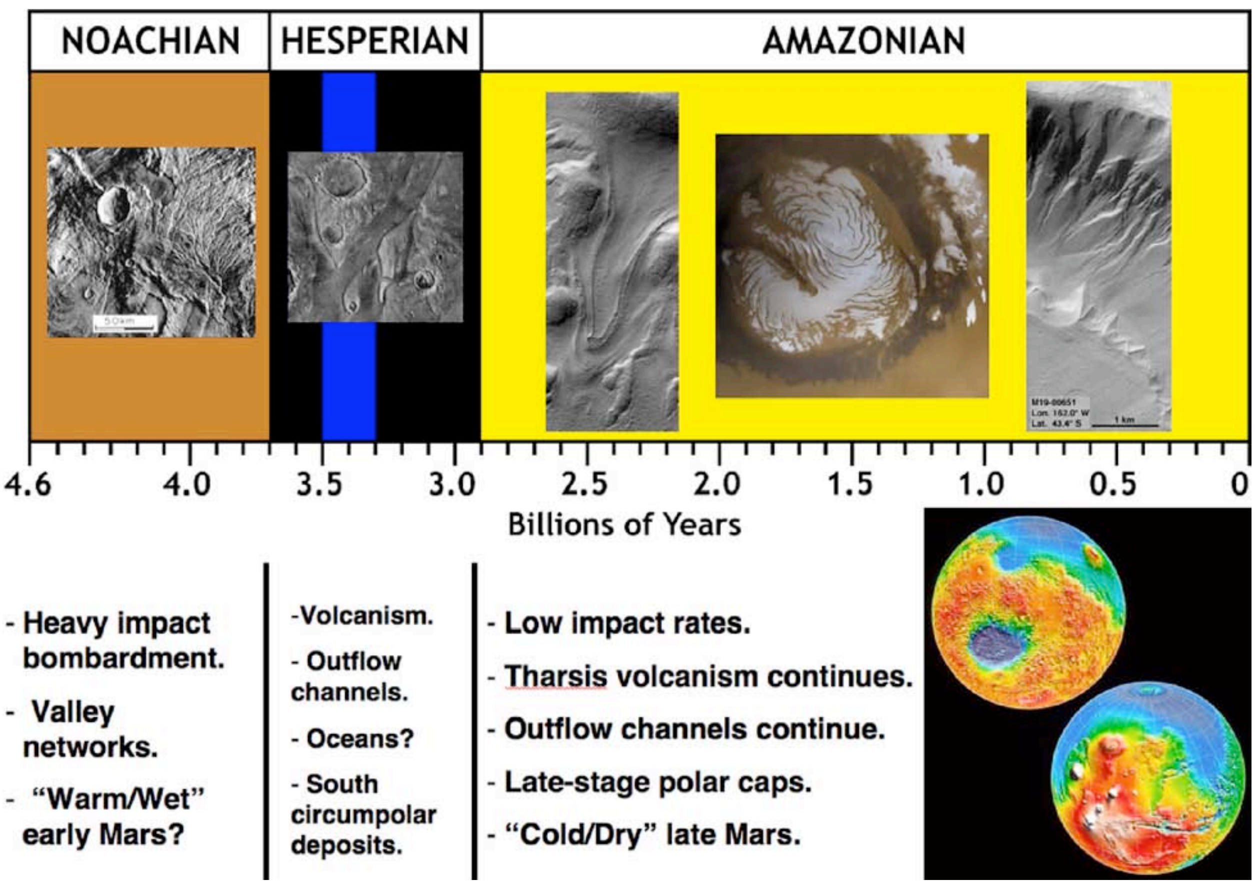

Figure 1. Geological history of Mars with the major periods and significant events and processes.

Thus, none of these questions could be answered by a focused study on just one landing site. The diversity of surface morphology and composition of the Martian surface demands an array of landing sites that spans the geologic history of Mars. As a preliminary exercise, we specified 58 distinct landing sites that would address these issues and would specifically benefit from the presence of human explorers (Figure 2). A brief discussion of each of the 58 landing sites is found in Appendix 1. From these 58 sites, we chose 3 sample sites for more detailed examination and traverse selection, which we plan to use as reference missions after further outlining the major questions with regard to the geology of Mars.

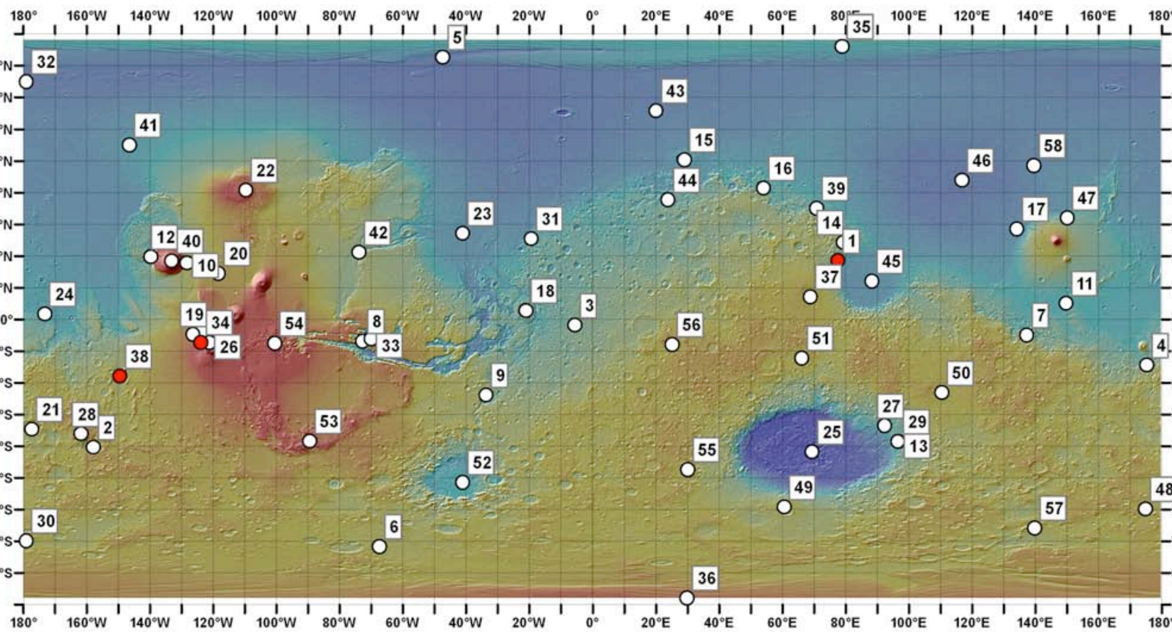

Figure 2. Location map for the 58 potential exploration sites on Mars.
The three proposed reference mission sites are indicated in red.

Planetary-Scale Geologic Processes that Could be Addressed by Human Exploration

The absolute ages of surface units on Mars has been deciphered through indirect methods; samples returned from the Moon in the Apollo Program were used to provide constraints on the crater-size-frequency distribution of the lunar surface, and this has been applied to Mars, among other terrestrial planetary bodies. While this has provided a general history of Martian surface processes (Figure 1), it does not allow for detailed study of specific Martian periods, in particular the Hesperian and Amazonian, when the impact flux greatly decreased. While Martian meteorites have been analyzed and dated, not knowing their geologic context makes their incorporation into the geologic history of Mars difficult. And while a Mars Sample Return mission would yield surface samples with known context, a robotic mission would not yield the array of optimal samples that would address a wide range of fundamental questions. A human mission would allow for greater access to samples that a robotic rover might not get to, and the capacity for real-time analysis and decision-making would ensure that the samples obtained would be the optimal samples available.

Human explorers would also have greater access to the near-subsurface of Mars, which would yield insights into climate and surface evolution, geophysics, and potentially biology. Humans would be able to navigate more effectively through blocky ejecta deposits that would provide samples that were excavated from great depth and provide a window into the deeper subsurface. Humans could trench in dozens of targeted locations and operate sophisticated drilling equipment that could sample the top ~1 km of the crust. Our current understanding of the crust of Mars is limited to the top meter of the surface, so drilling experiments would yield unprecedented and immediate data. Drilling in areas of gully formation could also test the groundwater model by searching for a confined aquifer at depth.

Human Science Reference Mission (HSRM): Geology

We have analyzed three different exploration sites in detail as potential reference missions for the first program of human Mars exploration. The sites would span the geologic history of Mars (one site for each period of Martian history; Figure 1) and allow for exploration traverses that would examine a variety of surface morphologies, textures and mineralogies to address the fundamental questions posed by MEPAG.

Jezero Crater. Jezero crater is a ~45 km impact crater on the northwest margin of the Isidis impact basin, in the Nili Fossae region of Mars (Figures 3 and 4). This region is a very important area for understanding the formation of the Isidis basin, the alteration and erosion of this Noachain basement, and subsequent volcanism and modification (e.g., Mustard et al., 2007; Mangold et al., 2007). The rim has been breached in three places: twice where channels from the neighboring highlands to the west have drained into the crater from the northwest (Figures 3, 4), and once on the eastern margin where the crater has drained eastward towards the Isidis basin (Fassett and Head, 2005) (Figure 5). Each input channel deposited deltas on the crater floor that have been preserved and reveal sedimentary structures (Figure 6) and clay deposits (Figure 7) in high-resolution images and spectral data (Fassett et al., 2007; Ehlmann et al., 2007). Other parts of the crater floor appear to have been resurfaced by lava.

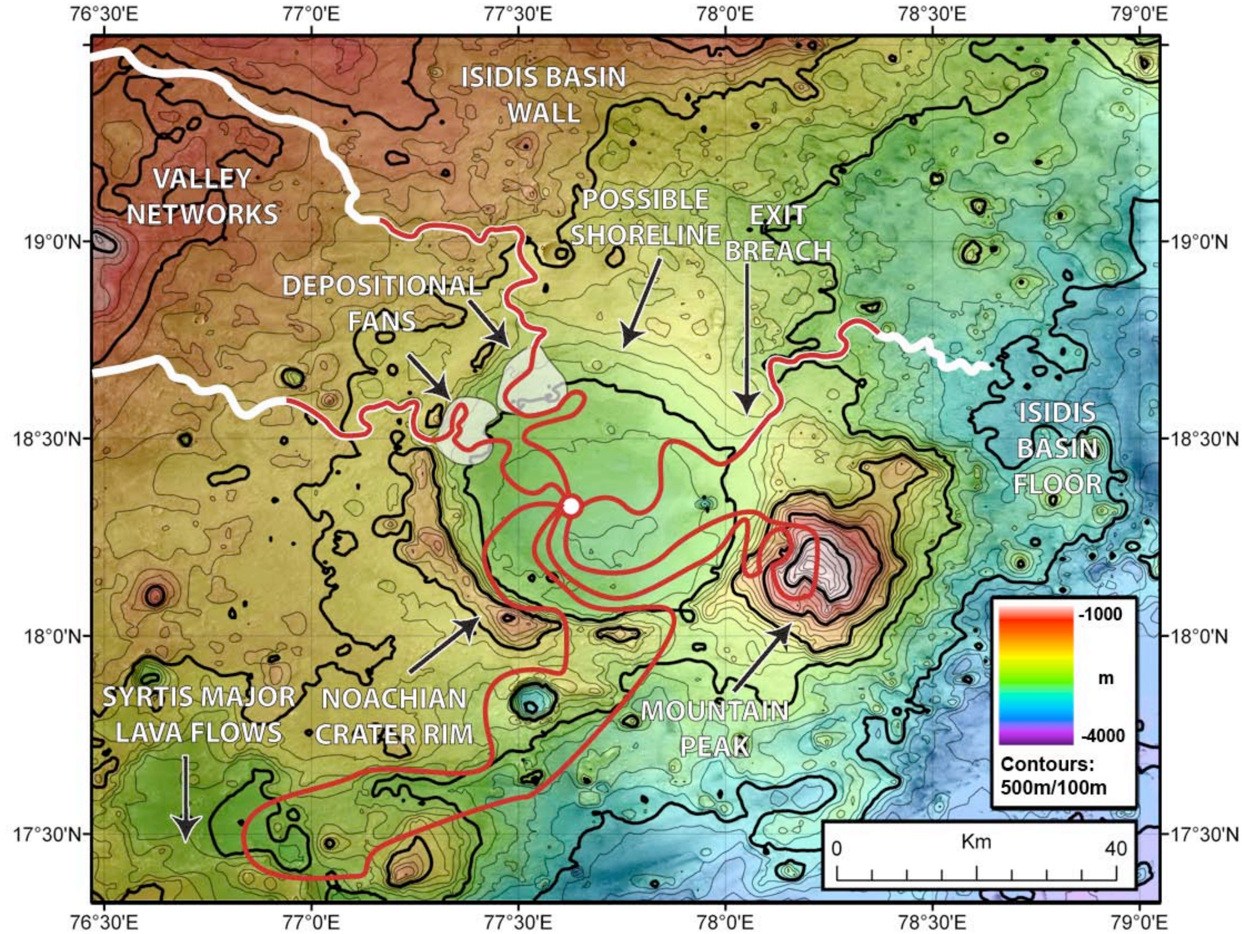

Figure 3. Potential traverses for human explorers in and around Jezero Crater.

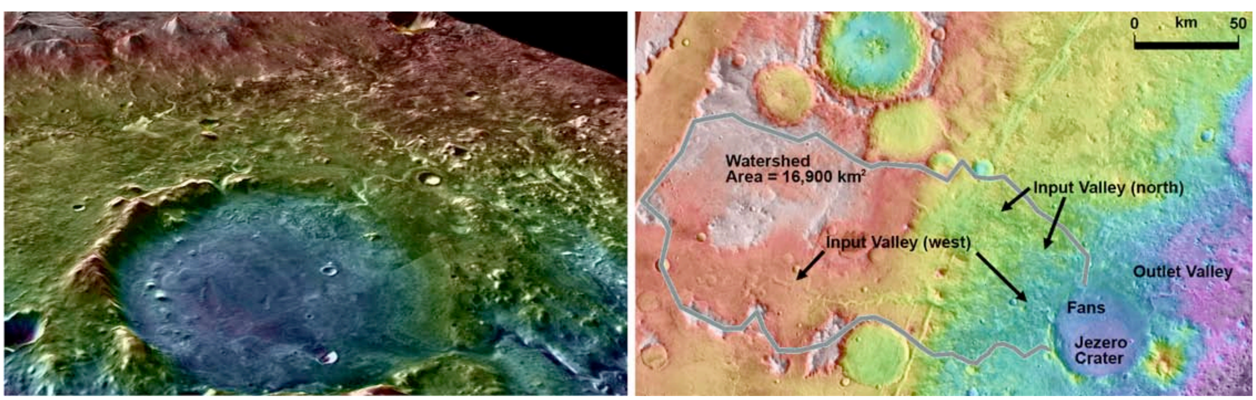

Figure 4. Jezero Crater in perspective view showing Isidis Basin rim and watershed area.

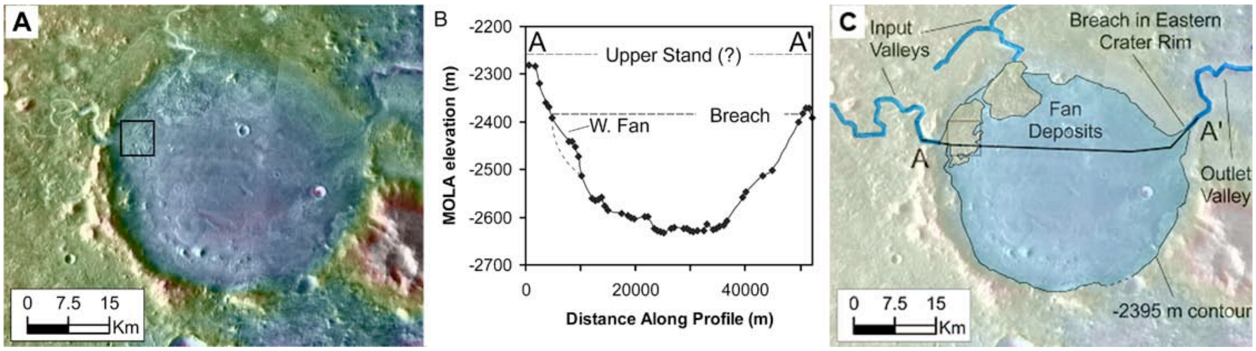

Figure 5. Topography of Jezero Crater.

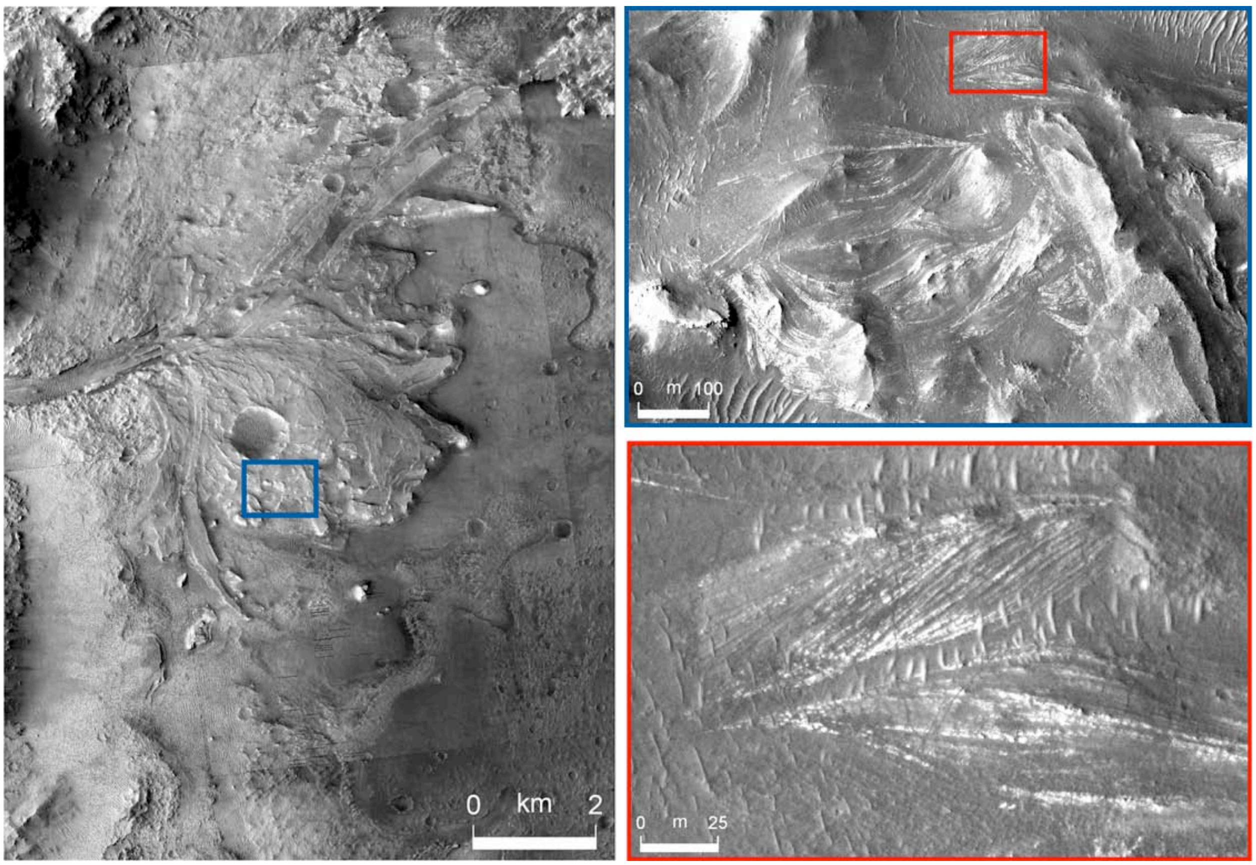

Figure 6. HiRISE image of delta deposit and layering in scroll bar.

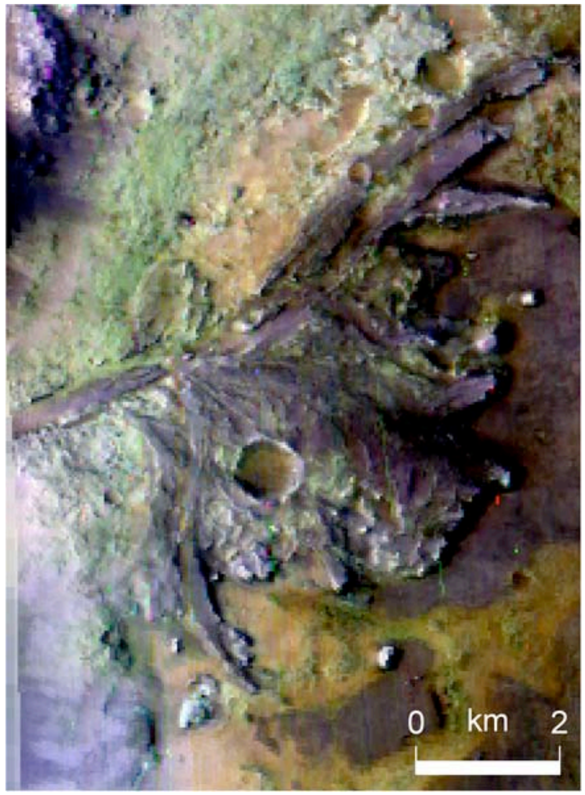

Figure 7. CRISM multi-spectral map of delta:
Green, phyllosilicates; Orange, olivine; Purple, neutral or weak bands.

A 500-day mission at this site would reveal considerable data regarding the early Martian environment. Jezero crater itself is Noachian in age and the preserved rim would provide access to ancient bedrock material (rich in low-calcium pyroxene) exposed by the impact. The delta deposits are likely to be Noachian in age and HiRISE data show that the sedimentary record in the deposit has been preserved as a series of thin layers (Figure 6). On the basis of the fact that a standing body of water existed within the crater for an extended period of time, this would be an ideal site to search for extinct biology. Humans would also be able to examine the structure and deposits within the channels associated with the deltas, which would be applicable to the other vast valley networks on Mars.

Extended traverses would be able to access and study the entire Jezero crater system (Figure 3). To the southwest of Jezero are Hesperian lava flows from Syrtis Major, a principle volcano in the northern hemisphere of Mars providing a key constraint on the geological timescale of the region. This would also shed light on the evolution of magma composition on Mars. To the east of Jezero is the floor of Isidis basin, which is topographically connected to the northern plains and which would allow for detailed study of major impact events. Samples collected from all of these sites would allow for enhanced geochronology and a more detailed understanding of the hydrology, sedimetology, volcanology, and habitablity of the region.

Mangala Valles. Mangala Valles is an Hesperian-aged outflow channel which has received considerable attention on account of its role in global cryosphere/hydrosphere interactions, as well as the possibility that it contains icy near-surface deposits (Levy and Head, 2005; Leask et al., 2007a,b; Hanna and Phillips, 2006; Ghatan et al., 2005; Wilson and Head, 2004; Head et al., 2004; Hanna and Phillips, 2007; Leask et al., 2007). Mangala Valles emanates from a graben that is radial to the Tharsis volcanic complex (Figure 8). Massive release of water from the ground at the graben was accompanied by phreatomagmatic eruptions (Wilson and Head, 2004) and caused catastrophic flow of water to the north, carving streamlined islands. There are also young glacial deposits along the rim of the graben (Head et al., 2004) and evidence for glacial scour having modified the surface of the outflow channel.

This site shows evidence for fluvial, volcanic, tectonic and glacial activity and complicated interactions among them. A landing site in the smooth terrain at the center of the outflow channel would provide access to a variety of sites of interest. Traverses to the channel head and the graben would allow direct observation of cryosphere-breaching geological activity. Traverses along the floor of the outflow channel, as well as on the scoured plains would provide insight into outflow flood hydrology and erosion processes, as well as provide an opportunity for sampling ice-rich deposits which may contain ancient flood residue. A traverse to the vent-rim glacial deposits would provide access to landforms created by volcano-ice interactions, as well as to samples of distal Tharsis volcanic deposits. On the basis of the likelihood that if life exists on Mars, it is most likely to inhabit the subsurface, a site such as Mangala would offer a unique opportunity to sample for evidence of such activity.

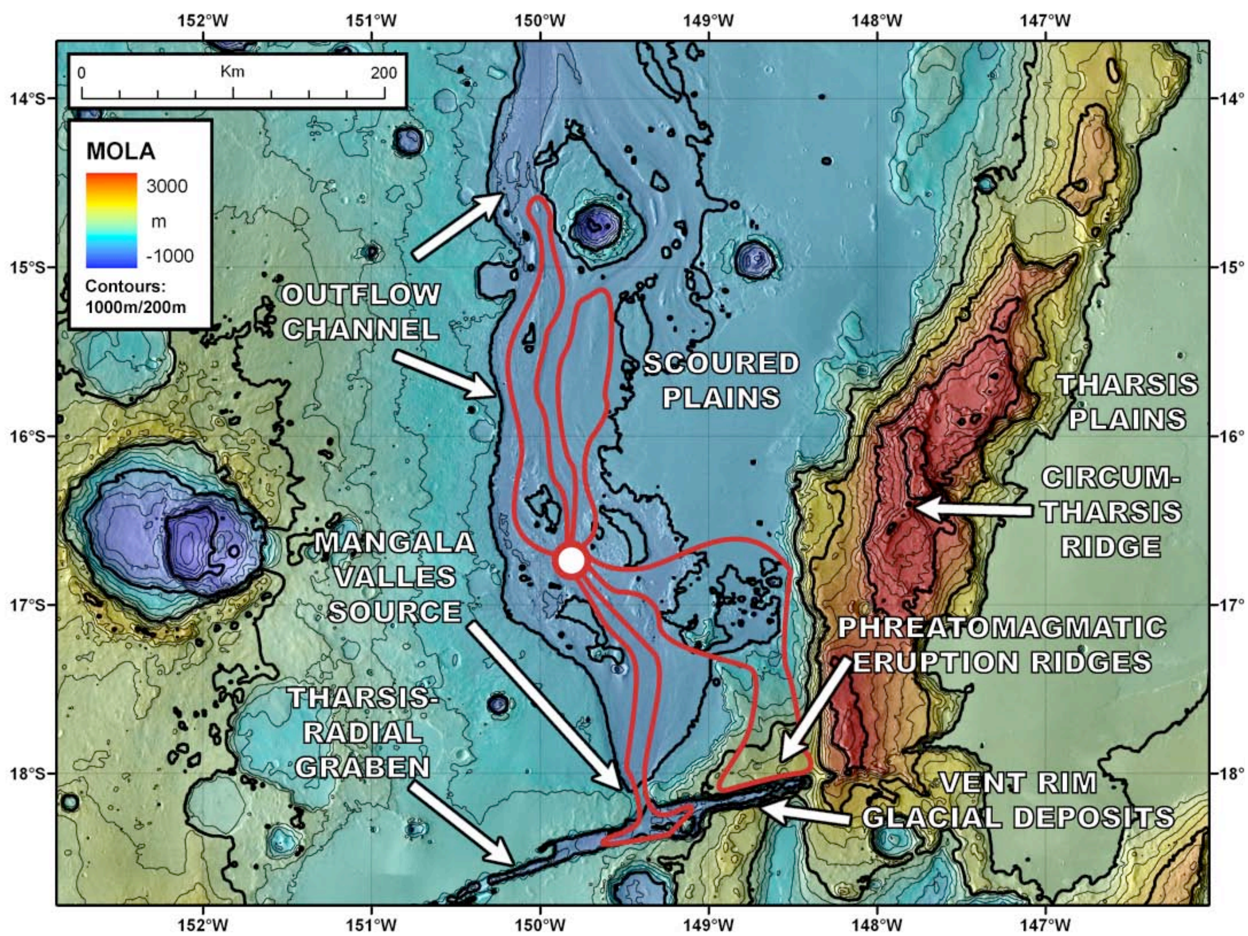

Figure 8. Potential traverses for human explorers in and around Mangala Valles.

Arsia Mons Graben. All three of the major Tharsis Montes shield volcanoes and Olympus Mons exhibit expansive late-Amazonian glacial deposits on their northwestern flanks. The broadest of these deposits are the ones found on Arsia Mons, which show glacial deposits ~400 km to the west of the accumulation zone and cover an area of about 170,000 km^3 (Head and Marchant, 2003). These glacial deposits are found among classic volcanic and tectonic structures, so an extended mission at this location would provide a wealth of information concerning several of the fundamental questions of Martian geology during the Amazonian period.

We designed several traverses from a potential base camp set up at 8°S, 124°W (Figure 9) that would analyze the glacial and volcanic deposits, and the complicated relationship between them. Using extended rovers human explorers would be able to ascend the western flank of the shield and systematically obtain targeted samples that elucidate the recent volcanic history of Arsia. Another traverse from the same base camp would provide access to a ~5 km wide graben that appears to have been a major accumulation zone for much of the observed glacial deposits (Shean et al., 2007). A systematic sampling strategy at this location would provide a history of the flow regime at this site, and drilling at targeted locations could provide the recent climate record for Mars.

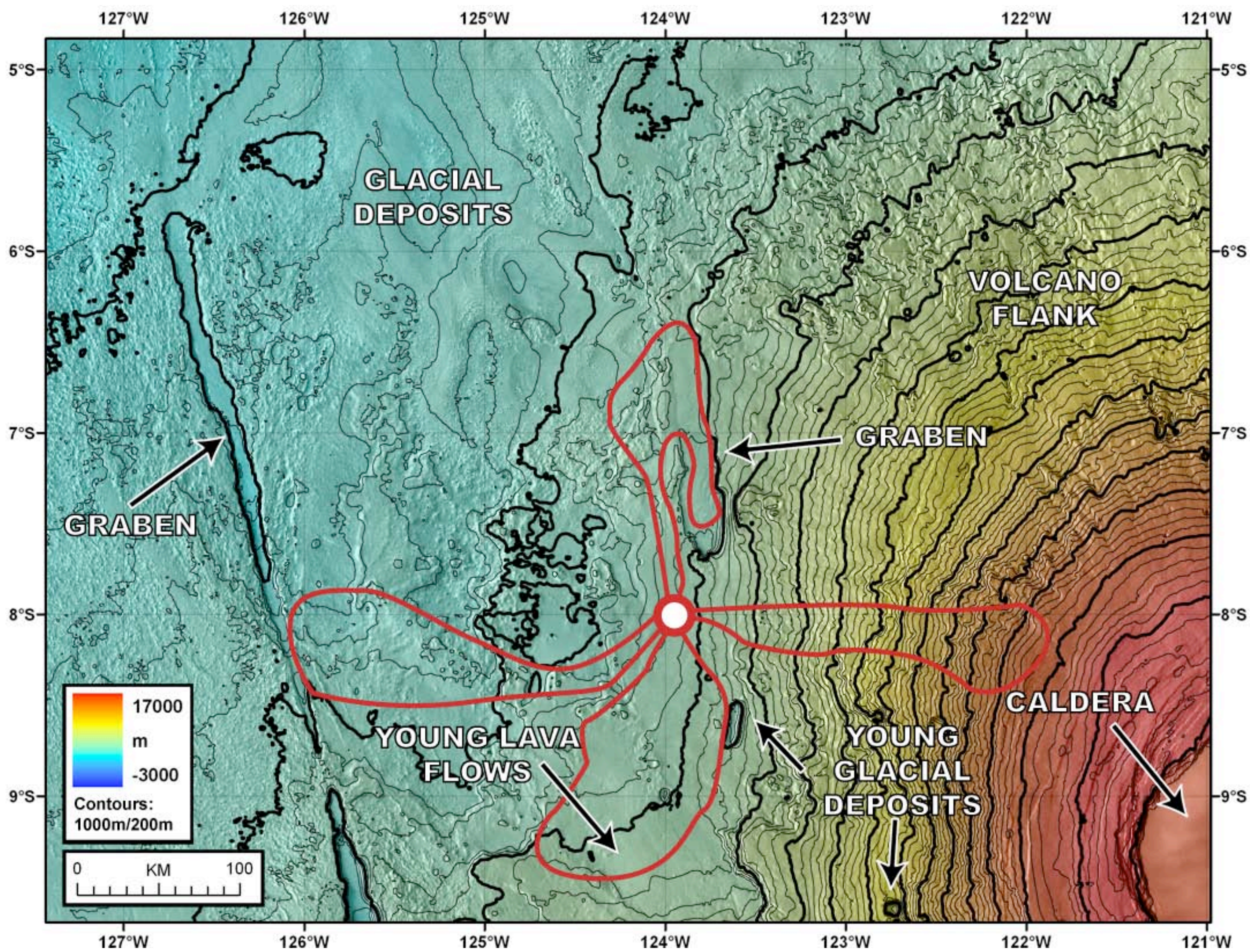

Figure 9. Potential traverses for human explorers in and around the Arsia Mons glacial deposits.

Recent General Circulation Models (GCMs) based upon global topography have revealed the Tharsis Montes to be significant cold traps for the accumulation of volatiles on the surface (Forget et al., 2006). Fieldwork at this site used in conjunction with remote sensing data would have global implications for recent climate change on Mars.

Below we assess the detailed activities that might be undertaken during these extended exploration periods, and show how they might link to MEPAG Goals and Objectives.

Graben and Surrounding Smooth Plains — 5 months

Geological Analysis. Analysis of glacial landforms and glacial and climatic history. Analyze the multiple drop moraines and assess sedimentary fabric, lithologic variations, search for erratics from further up the volcano. Study the processes producing drop moraines and assess similarities and differences between moraines. Dig for buried ice for ancient ice samples, and assess for ice cores for climate history. Examine the relationship to any exposed bedrock, searching for any evidence that the glacier was ever wet-based (scou in rock, drumlins, etc.). Examine thickness and fabrics of sublimation tills. Enter the major graben from the north, and traverse the ridges to the apparent base of the accumulation zone. Sample the volcanic rock suite and look for diversity and evidence of different eruption styles. Assess wall stratigraphy and gather representative samples in sequence for radiometric dating. (MEPAG investigations IA1, IA2, IA3, IIA2, IIB4, IIB5, IIIA1, IIIA3, IIIA4, IIIA5, IIIA6).

Shallow Seismic Survey. Measure thickness of sublimation tills and graben fill deposit at distal and proximal locations; assess presence of ice beneath till on graben floor. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Sediment Drilling. Analyze contributions from Arsia (tephra and bedrock) and from regional climate system (dust and ice) (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

GPR Ice-sounding. Determine high-resolution layering of valley-ill deposit, and document lenses of near-surface ice. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Shallow Excavations. Sample near-surface ice and permafrost deposits. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Electrical Resistivity. Determine permafrost depth in valley fill deposit and on surrounding plains. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2)

Rock Sampling. Systematic sampling to provide constraints on flow rates and evolution with implications for recent climate change. (MEPAG investigations IA3, IIIA2)

Mapping. Features of interest would include accumulation zone at the south-eastern extent of the graben and parallel ridges throughout the graben. Detailed maps of the extent of each of the major drop moraines. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2)

Eastern Flank of Arsia Mons — 3 months

Geological Investigations of the Flank of a Major Shield Volcano on Mars. Anaysis of mineralogy and petrology of lava flows, pyroclastic edifices and tephra deposits. Examine evidence for volcano-ice interactions and document geologic effects and chemical/mineralogic alterations. Look for evidence of the highest topographic levels of ice accumulation on the edifice and document the nature of such deposits. (MEPAG investigations IIIA4)

Mapping of the Flanks of a Representative Tharsis Volcano. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2)

Installation of sensitive seismometers to detect current magmatic and deeper subsurface activity and to study the internal structure of the volcanic edifice. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2)

Rock Sampling. Systematic sampling of Amazonian volcanic units to provide insight into present Mars composition. (MEPAG investigations IA3, IIIA2)

Southern Young Glacial Deposits — 3 months

Geological Analysis. Study the nature of the youngest glacial deposits in and around the small graben and assess the drop moraines and their stratigraphic relationships. Assess the ages of these in relation to the rest of the Arsia tropical mountain glacier deposits. Traverse the broad Arsia lava flows that appear to be superposed on the glacial deposit and assess their ages in detail, sampling for radiometric ages. Look for evidence for volcano-ice interactions and document these effects, including generation and fate of any meltwater. Assess impact craters for deeper material and subglacial deposits. (MEPAG investigations IIIA3, IIIA4).

Shallow Seismic Survey. Determine relative contributions of glacial and volcanic deposits. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Sediment Drilling. Examine sediment for compositional analysis. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

GPR Ice-sounding. Determine high-resolution layering of smooth glacial units, and document lenses of near-surface ice. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Shallow Excavations. Sample near-surface ice and permafrost deposits. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Electrical Resistivity. Determine permafrost depth in young glacial deposits. (MEPAG investigations IA1, IA2, IIB5, IIIA1, IIIA2).

Ice Coring. Drill to reveal ice composition and trapped atmosphere for recent climate change analysis.

Western Deposits — 4 months

Geologic Analysis. Traverse to major graben within the fan-shaped tropical mountain glacier deposit. Compare these glacial deposits to relatively younger deposits higher on the edifice. Assess proportions of sediment sources and determine depth to ice. Look for evidence of wet-based glacial activity. Traverse to graben: Analyze theories of origin. Compare evidence for simple glacial-passive graben interaction and the possibility of dike intrusion into the ice and phreatomagmatic explosions and eruptions. Look for country rock blocks and juvenile magmatic material on the rim and floor of the graben. Assess wall stratigraphy. (MEPAG investigations IA1, IIIA4, IIIA7).

Detailed Mapping of Glacial/Volcanic Interactions. (MEPAG investigations IIIA4, IIIA6, IIIA7).

Shallow Seismic. Record depth measurements of distal smooth facies. (MEPAG investigations IIIA4, IIIA5, IIIA6, IIIA7).

Rock Sampling. Dating of distal units to provide context for duration of glacial flow. (MEPAG investigations IIIA4, IIIA5, IIIA6, IIIA7).

Application to MEPAG Goal III. Determine the evolution of the surface and interior of Mars.

All of the investigations outlined by MEPAG Goal III could be addressed by human exploration at carefully chosen exploration sites, such as those at the here proposed reference missions outlined above. The following table shows the methods and instrumentation that would be used at the various exploration sites.

Table 1. Objective: Determine the Nature and Evolution of the Geologic Processes that Have Created and Modified the Martian Crust and Surface (Investigations In Priority Order)

Investigation	Geology Approaches
1. Determine the present state, 3-dimensional distribution, and cycling of water on Mars.	- Drilling - Surveying for groundwater seeps - GPR - MET Stations
2. Evaluate fluvial, subaqueous, pyroclastic, subaerial, and other sedimentary processes and their evolution and distribution through time, up to and including the present.	- Sampling along traverses - MET stations - In-situ composition analysis
3. Calibrate the cratering record and absolute ages for Mars.	- Thorough sampling of diverse rocks - Cosmogenic age dating of samples
4. Evaluate igneous processes and their evolution through time, including the present.	- Extensive sampling traverses - In-situ composition analysis
5. Characterize surface-atmosphere interactions on Mars, including polar, Aeolian, chemical, weathering, mass-wasting and other processes.	- MET stations - Traverse sampling along glaciers - Sampling of diverse mineralogy
6. Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations. This includes, for example, the structure and origin of hemispheric dichotomy.	- Drilling. - Seismic stations - GPR - Compositional comparison of fresh/weathered samples
7. Document the tectonic history of the Martian crust, including present activity.	- Seismic stations - Observations of graben and other tectonic features
8. Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present.	- Stratigraphic sample collection - Compositional analysis at multiple sites
9. Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes.	- Sample collection at multiple latitudes/environments - MET stations
10. Determine the nature of crustal magnetization and its origin.	- In-situ magnetometer analysis. - Traverses in areas of magnetic anomalies
11. Evaluate the effect of impacts on the evolution of the Martian crust.	- Ejecta sampling - Mapping of crater-wall outcrops