Groundbreaking Sample Return from Mars:
The Next Giant Leap in Understanding the Red Planet

A White Paper for the NRC Planetary Science Decadal Survey, Reflecting the Viewpoints of the NASA Analysis Group CAPTEM (Curation and Analysis Planning Team for Extraterrestrial Materials)

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*This white paper has been posted on the CAPTEM website noted above and inputs to it were sought from the planetary science community at large. Numerous comments and suggestions were received from many members of this community, and resulted in substantial revisions and endorsements to this white paper.

Introduction

Sample return is among the most important goals of Mars science (NRC 2003; MEPAG NDSAG 2008; iMARS 2008). "The Mars Panel attaches the greatest importance to Mars Sample Return …" (NRC 2003).

Mars Sample Return appears complex and expensive, so simple and less-expensive architectures are worth analysis. One such architecture is Groundbreaking MSR: a simple lander, without precision landing, carrying only sampling devices (e.g., arm + scoop, small drill, fetch rover), imager(s), and a rocket to return the samples toward Earth (MacPherson et al. 2002, 2005; Mattingly et al. 2005). To be effective, the lander must target a site of broad, uniform materials, characterized well by prior spacecraft. A Groundbreaking MSR mission in the next decade would address most of the science goals for MSR, **including astrobiology goals** (MEPAG NDSAG 2008, iMars 2008), and leverage the superb data in hand from orbiter and lander spacecraft (e.g., MERs, MRO, Mars Express). The cost of Groundbreaking MSR is probably consistent with a single flagship mission.

In this whitepaper, we describe the Groundbreaking architecture, and recount advantages and goals of sample return. To prove the Groundbreaking concept, we then show that sample return from either MER landing site (Meridiani Planum or Gusev Crater) would enable significant paradigm-altering science and satisfy many stated science goals for MSR. ***Thus, we recommend that the Planetary Decadal Survey Mars Panel consider the advantages of simple MSR, and request an independent cost analysis of a Groundbreaking MSR architecture***.

Groundbreaking Mars Sample Return

The concept of Groundbreaking Mars Sample Return was developed by MacPherson et al. (2002, 2005) under charter by MEPAG to define sample return mission architectures of low cost and complexity. Earlier architectures for MSR included heavily instrumented long-range rovers, which were costed at ~$3bn in '02 dollars. MacPherson et al. (2002, 2005) solved these issues by an architecture that ONLY returned samples, without precision landing, extensive roving, and complex instrumentation. In effect, this architecture pushes the data collection and decision making for sample collection to other spacecraft.

Groundbreaking MSR was envisioned as a lander carrying only a sample collection arm, a color imager, and a sample return rocket (MacPherson et al. 2002). The MER landings showed this architecture to be too restrictive. The Opportunity lander came to rest in a small impact crater, surrounded by rock outcrops at the crater rim, but with no rock accessible to an arm. In response, the Groundbreaking architecture was modified to include options of a small fetch rover (like Pathfinder) and/or a small drill (MacPherson et al. 2005).

The enhanced Groundbreaking mission was endorsed by the sample science community through CAPTEM (2008) with these findings: "For the first Mars sample return mission, a simple approach as advocated by the MSR SSG II [= McPherson et al. 2005] … provides the potential for successful science." "A sample collection strategy that will reduce overall time on the Martian surface will reduce cost and risk to a sample return mission." "There is a plethora of important science that can be accomplished with a simple MSR mission (with mobility ≤ 1 km) to a previously visited site."

The Groundbreaking Sample

The Groundbreaking MSR concept assumes that scientifically crucial materials can be defined by prior spacecraft elements, and that samples of those materials can be located without precision landing or complex instrumentation. Thus, Groundbreaking MSR is constrained to targeting easily recognized materials that are widely distributed, e.g. the global dust, an extensive lava unit, a widespread sedimentary unit, etc. (e.g., Jones and Treiman 1998; Jones 2008; Neal 2008; Shearer et al. 2008).

Why Return Samples from Mars?

Mars is a unique target in planetary exploration. Being somewhat Earth-like, Mars is a crucial point of comparison for understanding the origin and evolution of Earth. Much of Earth's early history, so important for understanding its path to the current dynamics and climate, has been lost through its active tectonic and sedimentary cycles. Mars retains rocks and surfaces from that early time period, which spans the apparent beginnings of life on Earth. Thus, Mars seems the best, most accessible place in the Solar System for investigating pre-biotic chemistry and the rise of habitable environments such as occur Earth.

Sample return has an essential place in understanding Mars, and in addressing the goals of Mars science listed below (NRC 2003; MEPAG NDSAG 2008; iMARS 2008). In laboratories on Earth, returned samples can be analyzed with quality, scope, flexibility, and potential for the future that cannot be attained by *in situ* spacecraft analyses (Jones and Treiman 1998; MacPherson et al. 2002, 2005)

Quality

The analytical precision and accuracy obtainable in modern Earth-based laboratories exceeds that of the best spacecraft instruments, because the former offers unlimited availability of: resources, environmental controls, operator intervention, and sample preparation. Earth-based instruments can be designed for nearly unlimited resources, while spacecraft instruments are severely restricted by available energy, volume, time, CPU power, memory, data rate, etc. Earth-based instruments can be delicate and be housed in benign environments (e.g., fixed temperature, low vibration, free of magnetic fields), while spacecraft instruments must survive shocks, temperature extremes, vacuum, hard radiation, etc. Earth-based instruments can be optimized, tended, and fixed in real time by skilled technicians, while spacecraft instruments must work 'as is' without repairs. Finally, Earth-based instruments can be designed for specialized samples (e.g., polished thin sections or thinned TEM mounts) prepared in complex laboratories, while spacecraft instruments must include sample preparation or do without (Gooding et al., 1989). Earth-based analyses will benefit from advancing technology and continuous improvements (e.g., SIMS for Genesis samples). Given the timelines of spacecraft design and construction, flight instruments can be 10-15 years out of date when they arrive at their destination. With these advantages, it is no surprise that Earth-based instruments out-perform the best spacecraft in detailed and micro-analytical tasks required to achieve the science objectives discussed here.

Scope and Flexibility

Earth-based analyses of returned samples are essentially unlimited in scope and flexibility – with all Earth laboratory instruments available, one can analyze a returned sample for any sort of structural features, element abundance, isotope ratio, or complex compound. Further, that feature or abundance or ratio can be re-analyzed to increase precision, if needed. On the other hand, spacecraft investigations are necessarily limited in scope and flexibility. A spacecraft has limited and invariant instrumentation – it does no good to wish, for instance, that the MER rovers now on Mars could analyze for amino acid abundances and chiralty. Similarly, the instruments on a spacecraft, far from Earth and technical support, cannot be altered to respond to unexpected findings.

Future Investigations

A returned planetary sample is a gift that keeps on giving. It can be studied for generations to come, analyzed and re-analyzed as methods improve and as new scientific questions arise. And although not a substitute for additional sampling missions, having returned samples means that a new mission is not required whenever a new analytical technique is invented or scientific concept arises.

Martian Meteorites

The current collection of Martian meteorites is very useful for addressing some, but not all scientific questions. The ~ 50 known Martian meteorites are relatively fresh igneous rocks from basalt flows or shallow basaltic intrusions. However, many important scientific questions cannot be addressed through studies of the Martian meteorites because they do not include samples of sedimentary rocks, regolith, impact breccias, clay-rich rocks, sulfate-rich rocks, hydrothermal deposits, or even evolved igneous rocks (all of which have been identified from imagery and spectroscopy). These missing samples include all types most likely to provide significant information about habitable environments and/or life on Mars. And, only one of the Martian meteorites is ancient (ALH 84001). Finally, the scientific value of Martian meteorites is limited because we do not know where they formed, and so cannot be tied unambiguously to remote sensing data (Shearer et al. 2008).

Science Objectives for MSR

Several groups have refined science objectives for MSR; this was done most recently by MEPAG NDSAG (2008) and iMARS (2008). The objectives are repeated here (slightly condensed), as a metric for science return from 'proof of concept' Groundbreaking MSR missions.

1. Understand processes that could sustain habitable environments on Mars (today and in the past), by determining the chemical, mineralogical, and isotopic compositions of the crustal reservoirs of elements C, N, S, H, etc., elements with which they have interacted, and by characterizing phases containing these elements to submicron spatial scales.
2. Assess the evidence for prebiotic processes, past life, and/or extant life on Mars by characterizing the signatures of these phenomena in the form of structure/morphology, biominerals, organic molecular and isotopic compositions, and other evidence within their geologic contexts.
3. Interpret the conditions of water-rock interactions via their mineral products.
4. Constrain absolute ages of major crustal geologic processes, including sedimentation, alteration and diagenesis, volcanism/plutonism, regolith formation, weathering, & cratering.
5. Understand paleo-environments and the history of near-surface water on Mars by characterizing sedimentary sequences and their clastic and chemical components, depositional processes, and post-depositional histories.
6. Constrain the mechanisms and timing of planetary accretion and differentiation, and the subsequent evolution of the crust, mantle, and core.
7. Determine how regolith forms and is modified, and its variations in space and time.
8. Characterize risks to human explorers from biohazards, material toxicity, and dust/granular materials, and contribute to assessment of *in situ* resources in support of human presence.
9. Determine the preservation potential for the chemical signatures of extant life and prebiotic chemistry in the present surface and shallow sub-surface, by evaluating oxidation state as a function of depth, permeability, and other factors.

10. Constrain the early composition of the martian atmosphere, the rates and processes of atmospheric loss/gain over geologic time, and the rates and processes of atmospheric exchange with surface condensed species.
11. Determine the ages, geochemistries, conditions of formation, and evolutions of polar deposits, via detailed examination of the elemental and isotopic compositions of H_2O, CO_2, and dust constituents, and via detailed stratigraphy of the deposits.

'Proof of Concept' Groundbreaking MSR: MER Landing Sites

Groundbreaking MSR depends on detailed knowledge of a landing site, such that neither precision landing nor complex instrumentation are required of its mission architecture. Of course, sample return would require such information: "It is essential that the site to be sampled be carefully chosen, with the choice drawing on the large body of orbital and lander data that will be in place by the time MSR is flown" (NRC 2003). The MER landing sites, Meridiani Planum and Gusev Crater, are examples of such sites – each is well characterized through multiple orbital and *in situ* measurements, and a sample return from either site would address a significant number of the established goals of MSR. Here, as a proof of concept for Groundbreaking MSR, we briefly describe each of the MER landing sites in terms payoff from a sample return. Data returns are linked to the MSR goals above by numbers in brackets, like this [Goals 1-3,5].

Meridiani Planum

Return of regolith and rocks from Meridiani Planum (the MER Opportunity landing site) would yield paradigm-changing data on early Mars' sedimentary systems, sub-surface aquifers, and acid-sulfate environment (Mittlefehldt, 2008; CAPTEM, 2008). Meridiani Planum is underlain by a thick sequence of layered and cross-bedded sediments, interpreted by most as dune and inter-dune deposits (Squyres and Knoll, 2005). The sediments are rich in sulfate minerals, most notably jarosite (Clark et al. 2005), and contain spherules of hematite that may be diagenetic alteration products. The sediments contain void spaces that may have held crystals of another sulfate mineral, like gypsum or meridianiite. Chemically, the sediments are like basalt plus sulfate (Clark et al. 2005), suggesting that the original sediments were volcaniclastic, and were altered in place in by acid-sulfate solutions.

Sample return from Meridiani would provide breakthrough data on Mars' astrobiology, aqueous chemistry, and sedimentary environments. Common samples are discussed below. Regolith would include rock fragments and basaltic-composition sands that may be typical of regional eolian deposits across Arabia (e.g., Serpent dune) [Goal 7]. However, a small sample return of the jarosite-rich sediments of Meridiani would provide a wealth of information addressing a significant set of MSR goals. First, a returned sample of rock (e.g., a short drill core) would clarify the nature of the Meridiani deposits by examination of primary sedimentary structures and relict mineral grains [Goals 1,5]. Mineralogical and isotopic analyses of jarosite would especially important – one could determine the age of jarosite formation by Ar-Ar (Lueth 2006) [Goal 4], chemical and isotopic composition of the depositing fluids (Papike et al. 2006; Landis and Rye 2006; Stoffregen 2006) [Goals 1,3,5,7], temperature of alteration (Lueth 2006; Landis and Rye 2006), and possibly noble gas composition of the atmosphere (Landis and Rye 2006) [Goal 10]. Acid sulfate waters support several sorts of terrestrial biota which can become fossilized via mineralization (e.g., Fernandez-Remolar and Knoll, 2008) [Goals 1,2].

Gusev Crater

Return of regolith and rocks from the floor of Gusev Crater (the MER Spirit landing site) would yield paradigm-changing data on Mars' ancient history, its modern surface environment, and on subsurface environments. The Gusev Crater site is an intra-crater plain of basalt lava flows, and is littered with broken fragments of that basalt. The basalts there have been analyzed in situ as well as any planetary samples (McSween et al. 2006). The Gusev basalts are dark massive rocks, with thin weathering rinds, and thin coating of dust. On abraded faces, their interiors are mostly featureless, with common darker spots, a few void spaces, and thin veinlets of pale material. The veinlets are inferred to represent aqueous alterations and deposits. The basalts contain abundant olivine. The chemical analysis of Humphrey, of adequate precision (major and minor elements) for simple geochemical modeling, is consistent with basalt and secondary sulfate minerals; only a few trace elements abundances were determined.

Sample return from Gusev would provide breakthrough data on many aspects of Mars' geology, chemistry, and astrobiology. Common samples are discussed below. Local regolith might well contain sand-sized material from the Gusev's walls and adjacent highlands, and so would help constrain the nature of the highlands crust [Goals 4,7]. However, a small sample return of Gusev basalt returned to Earth would provide a wealth of information addressing nearly all of the MSR science goals. Radiometric ages of crystallization would provide a key anchor point for the crater count chronology of Mars (especially near the time of crucial environmental change at the Noachian-Hesperian boundary) and the inner solar system (Hartmann and Neukum 2001) [Goals 1-6]. Detailed chemical and mineralogical analyses on the basaltic materials, derived from the martian mantle, and on aeolian sands and dust components would contribute to determining the bulk composition of Mars, the size of its core, melting processes in the mantle and the composition of Mars' early mantle, abundances of volatiles (S, Cl, Ar, Xe) and the volcanic contribution to the martian atmosphere [Goal 10]. Gusev basalts are older than, and chemically distinct from, the martian meteorite basalts; comparisons among them would elucidate some of the evolution of the martian mantle, both for dynamics and differentiation (Li and Kiefer 2007; McSween et al. 2009) [Goal 6]. Understanding of Martian meteorites would be advanced by comparison with martian basalt that had not suffered shock ejection from Mars, exposure in space, and terrestrial weathering. Study of weathering rinds (Haskin et al. 2005) might reveal changes in Mars' climate – perhaps warmer and wetter than today [Goals 1-3,5].

For astrobiology, the major targets are the veinlets in the Gusev basalts. The veinlets likely formed by aqueous alteration (Haskin et al. 2005), and chemical interactions between water and olivine or basalt are known (on Earth) to provide the energy and nutrients for microbial life (Stevens and McKinley 1995; Hoehler 2005). Chemical and isotopic analyses of these veinlets, impossible by robotic *in-situ* instruments, would define the timing of alteration, the product minerals and their compositions, the compositions of altering water, and the availability of energy and nutrients to constrain habitability [Goals 1-3,5]. Bio-organic analyses would test for pre-biotic chemistry, and for traces of extant or ancient Martian life. And morphological examination would reveal biological structures, if present [Goals 1-3,5].

Common Samples: Atmosphere, Dust, Regolith

Groundbreaking sample return from either MER landing sites would include some materials common to, or characteristic of, the whole planet. Sample return would likely include some atmosphere, which would allow precise determination of its elemental and isotopic composition [Goals 1,6,10]. Some fraction of the global fine-grained dust would be included, Understanding the dust is crucial to many aspects of Mars science, including orbital remote sensing, atmospheric dynamics, atmospheric chemistry (e.g., as a possible catalyst for oxidation of methane), machine operability, and human health [Goals 1,3,4,7,8,10,11]. And regolith, while specific to each site, will include tracers of global processes such as: accretion of micrometeorites and interplanetary dust particles, with their characteristic elements, organics and noble gases (Flynn and McKay 1990; Flynn 1996, 1997); and erosion rates and atmospheric density (Arvidson et al., 1981) [Goals 1,7-10]. Return of regolith samples would also feed forward to eventually human exploration, in terms of health hazards and spacecraft operations [Goal 8].

Conclusion

The Groundbreaking architecture is a viable approach to Mars Sample Return; it can return samples of paradigm-changing geologic and astrobiologic significance from the well-characterized landing sites, such as those of the MER rovers, that address nearly all of the published goals of MSR. At either MER site, there would be no need for advanced instrumentation on the sample return lander, and only limited need for mobility. A Groundbreaking MSR mission has not been costed since 2001, and we suggest that the Decadal Mars Panel consider the Groundbreaking architecture seriously, and commission an independent engineering and cost estimate.

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