

APPENDIX II

Analysis of the use of returned Martian samples to support the investigations described in the MEPAG Goals Document.

Prepared by ND-SAG

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Note that the Goal, Objective, and Investigation headings plus the blue text are quotes from the 2006 MEPAG Goals Document, available on the MEPAG web site <http://mepag.jpl.nasa.gov/reports/index.html>.

I. GOAL: DETERMINE IF LIFE EVER AROSE ON MARS

A. Objective: Assess the past and present habitability of Mars

A1. Investigation: Establish the current distribution of water in all its forms on Mars

Team leads: *Des Marais, McLennan, Nealson*

Water on Mars is thought to be present in a variety of forms and potential distributions, ranging from trace amounts of vapor in the atmosphere to substantial reservoirs of liquid, ice and hydrous minerals that may be present on or below the surface. The presence of abundant water is supported by the existence of the Martian perennial polar caps, the geomorphic evidence of present day ground ice and past fluvial discharges, and by the Mars Odyssey GRS detection of abundant hydrogen (as water ice and/or hydrous minerals) within the upper meter of the surface in both hemispheres, at mid-latitudes and above. To investigate current habitability, the identity of the highest priority H₂O targets, and the depth and geographic distribution of their most accessible occurrences, must be known with sufficient precision to guide the placement of subsequent investigations. To understand the conditions that gave rise to these potential habitats it is also desirable to characterize their geologic and climatic context. The highest priority H₂O targets for the identification of potential habitats are: (1) liquid water -- which may be present in as pockets of brine in the near-subsurface, in association with geothermally active regions (such as Tharsis and Elysium), as super-cooled thin films within the lower cryosphere, and beneath the cryosphere as confined, unconfined, and perched aquifers. (2) Massive ground ice -- which may preserve evidence of former life and exist in a complex stratigraphy beneath the northern plains and the floors of Hellas, Argyre, and Valles Marineris, an expectation based on the possible former existence of a Noachian ocean, and the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity. (3) The polar layered deposits -- whose strata may preserve evidence of climatically-responsive biological activity (at the poles and elsewhere on the planet) and whose ice-rich environment may result in episodic or persistent occurrences of liquid water associated with climate change, local geothermal activity and the presence of basal lakes.

This investigation would help to explore the hypothesis that Martian life exists today. To support the search for evidence of currently habitable environments, the depth and geographic distribution of the most accessible liquid H₂O targets must be known with sufficient precision to guide mission site selection. This investigation would include both present-day water and evidence for recent liquid water. For example, samples that indicate aqueous activity during the geologically recent past (e.g., the most recent 100 million years) might demonstrate that habitable environments persist today in the subsurface.

Relatively recent habitats might include the following:

- (1) Liquid water in near-subsurface brines, in geothermally active regions, and as confined, unconfined, and perched aquifers beneath the cryosphere.
- (2) Massive ground ice that might have sustained habitable environments during recent climate changes, including those associated with excursions to higher obliquities.
- (3) Polar-layered deposits that might preserve evidence of liquid water associated with climate change, local geothermal activity and the presence of basal lakes.
- (4) Diurnal and/or seasonal water cycling during hydration-dehydration reactions of hydrous minerals (e.g. $\text{MgSO}_4 \cdot n\text{H}_2\text{O}$). (but is it a habitable environment? – not likely given the low water activities due to salinity and thin film behavior)

Important measurements would include the following:

- (1) Abundances of water in crustal materials, ices and atmosphere. These measurements would help to reconstruct crustal inventories and characterize the potential for recent habitability.
- (2) Oxygen and hydrogen isotopic compositions of these water reservoirs. Isotopic measurements would help to determine the sizes of these reservoirs and they also could help us characterize processes that exchange water between the atmosphere, crust, minerals and ice deposits.
- (3) Composition of salts or other species that might indicate the solute compositions and the water activities of any aqueous phases that existed during recent geologic epochs. The solute contents of water affect its capacity to sustain a habitable environment.

Because a Mars sample return mission could not access liquid water directly, it would be critical to document the geological and environmental contexts of the collected samples in order to infer the nature of any recent aqueous environments. For example, a sample from a rock ejected from a large impact crater during the geologically recent past might provide evidence that a subsurface aquifer exists even today. Salt deposits resulting from evaporation or sublimation of water could provide evidence of water transfer from the subsurface to the atmosphere. An icy sample would contain existing water. In all cases, samples require field observations to document their contexts and origins. The scales of imaging during a Mars sample return mission should range from orbital through rover panoramic camera to microscopic imager.

Sample types needed. Water-containing phases. Other materials that water has altered either physically or chemically might indicate water activity in the geologically recent past. These materials might indicate, for example, that habitable environments exist today in the deep subsurface or perhaps existed intermittently near the surface.

Sample diversity needed. A suite of samples that would allow collective characterization of both the geologically recent water reservoirs in the atmosphere, ices, regolith and deep subsurface and the processes that link these reservoirs.

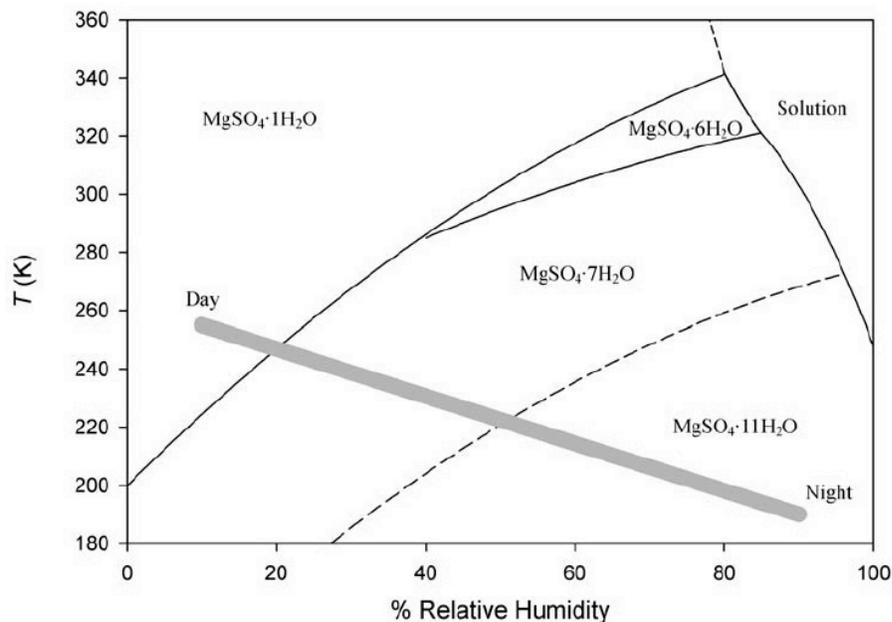
Physical condition (rock, pulverized rock, etc.). Intact rock samples, such as chips and cores, would be optimal because they best preserve any fluid inclusions, microtextural relationships or environmentally labile hydrated phases. Pulverized rock might be useful to identify relatively more stable hydrated phases if samples are not heated to the point where such phases are degraded. The same would apply to ice samples until they are hermetically sealed for return. Atmospheric water and trace gases that are quantitatively trapped and hermetically sealed also would add value to this investigation.

Contamination types and limits that affects this investigation. Water and any materials having exchangeable oxygen and hydrogen in spacecraft materials might affect the abundance and stable isotopic composition of hydrated samples. Amounts that exceed the equivalent of 1000 ppm water in the samples might substantially alter hydrated minerals present at the level of one weight percent in the samples and therefore could create potentially serious levels of contamination. The stable isotopic composition of any exchangeable oxygen and hydrogen in spacecraft materials should be characterized.

Sample number and mass. The requirements for mineralogical context, the expected abundances of hydrous phases and the contamination concerns call for individual sample sizes in the range 1 to 5 grams, especially in order to evaluate textural relationships. On the other hand, sizes on the order of ~1 gram or less should be sufficient for most chemical and isotopic analyses. A suite of ~5 samples would be desired to characterize variations in hydration and water-rock interactions.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Temperatures that exceed maximum Mars ambient temperatures at the site of sample collection are expected to alter any ices and also the most sensitive hydrated minerals. Partial pressures that are lower than those at minimum Mars ambient partial pressure would similarly cause degradation of these phases. Alteration of hydrous phases and ices would compromise some isotopic analyses and most textural analyses for samples with substantial water.

Maximum sample temperatures for sample integrity. Keeping samples below maximum Mars ambient conditions would achieve 100% of the objective. Sample handling and storage temperatures that exceed 50°C almost certainly would seriously degrade some samples that contain polyhydrated phases (e.g., see figure, below). Samples of ice should be kept below temperatures where they sublime rapidly after acquisition and before storage in hermetically sealed containers. Storage containers for all hydrous samples should be hermetically sealed.



Impact of degradation on the investigation. Elevated temperatures would alter phases perhaps to a point where the original hydrated phases could not be reconstructed. Loss of volatiles during

acquisition and handling might fractionate the composition of those that remain to the point where original isotopic compositions could no longer be inferred. At the very least, sealed sample containers coupled with sample characterization on Mars should maximize the possibility of “reconstructing” degraded samples.

Required/preferred sampling hardware. Rock and ice corers that achieve minimal heating during sampling would be required. Sample handling should heat the samples only minimally. Sample processing probably should be achieved outside the rover body to remain at or below Mars ambient conditions. The most thermally sensitive samples should be stored individually in hermetically sealed containers within one sol of sampling.

Data needed for sample choice and in situ characterization. Image the rock outcrop or regolith sampling site to document their macroscale textures and any indications of their composition and origin. Performing spectroscopic (NIR or MIR) and elemental abundance measurements to guide selection of optimal samples should be a priority. An *in situ* pyrolytic analysis of candidate samples could assay the abundance and composition of water or other key volatile species.

Estimate of required mobility range. This requirement would be very site-specific. High latitude sites on ice might require horizontal mobility ranging from zero to a few 100 meters, but drilling to depths of several centimeters to meters. Mid- to low-latitude sites might require mobility of several kilometers to access sample diversity.

Additional comments. Hydrated or water-containing samples tend to be sensitive to elevated temperatures or prolonged exposure to conditions where water vapor pressure is lower than in their original environments. These samples should be acquired and processed at or below maximum local ambient conditions. Sensitive samples should be stored in hermetically sealed containers as soon as possible. There should be capability for sealing samples as quickly as possible, preferably within minutes to hours if needed but certainly within one sol. They would require similar confinement and storage conditions in the sample receiving facility on Earth.

A2. Investigation: Determine the geological history of water on Mars, and model the processes that have caused water to move from one reservoir to another.

Team leads: *Des Marais, Carr, McLennan, Grady, Westall*

In order to assess past habitability, we need to start with understanding at global scale the abundance, form, and distribution of water in Mars’ geologic past. A first-order hypothesis to be tested is that Mars was at one time warmer and wetter than it is now. This could be done in part through investigation of geological deposits that have been affected by hydrological processes, and in part through construction of carefully conceived models. One key step is to characterize the regional and global sedimentary stratigraphy of Mars. It is entirely possible that Mars had life early in its history, but that life is now extinct.

The aqueous history of Mars can be divided into three eras: (1) the Noachian for which we have evidence that suggests widespread episodic precipitation and the consequent fluvial erosion, lacustrine sedimentation, weathering and groundwater activity, (2) the post-Noachian which is characterized largely by dominantly dry conditions punctuated by episodic floods widely spaced in time, and (3) the recent geologic past for which the water story is dominated by gully formation, glacial activity, thin aqueous alteration rinds on exposed surfaces and changes at the poles.

Noachian era (4.1-3.7 Gyr ago). This is the era for which we have the best and most abundant geomorphic evidence for warm climatic conditions. Desired samples include sediments from deltas, and from layered sequences both in local lows such as craters and from the more extensive Noachian 'etched' terrains. Samples should include both clastic and chemical sediments, and be taken from as diverse a suite of stratigraphic horizons as is practical. Sedimentary structures, the size, sorting and rounding of grains, and the distribution of soluble minerals would all help understand the environment under which the sediments accumulated. Also desirable would be samples rich in possible weathering products such as phyllosilicates. Sequences of samples from soil profiles would be particularly important for determining climatic conditions under which the soil profiles formed. Given the high rates of volcanism and meteorite impacts and seemingly widespread presence of water in Noachian times, hydrothermal activity was likely. Should any such sites be found they would be of high priority for sampling. Other possible samples that would complement the more accessible upper Noachian samples are samples from sections deep within the Noachian, such as those at bases of cliffs in eastern portions of canyons dissecting Noachian-aged rocks. Finally, sediments from the Noachian near the south pole may preserve a record of conditions at the poles during this early era, and should Noachian marine deposits be identified, they would be strong candidates for sampling.

Middle Mars History (3.7 Gyr to 0.1 Gyr ago). This era encompasses most of the history of the planet and is characterized by extremely low rates of weathering and erosion, formation of the canyons, formation of most of the planet's large flood features and the possibly the consequent episodic accumulation of large bodies of water. In addition, ice-abetted processes appear to have been pervasive in mid to high latitudes. The era appears to have been mostly dry and cold. Key water-related issues are whether there were any short, warmer, climatic excursions and if so when they occurred, how long they lasted, and whether there were ever large standing bodies of water in enclosed areas such as the canyons, Hellas and the northern plains. As with the Noachian, the most valuable samples for understanding the water story would likely be sediments. Possibly the thickest sequence of stratified sediments so far identified from this era are within the canyons. Some of these post-Noachian sediments are eroded by young valley networks. Samples would be needed from both the stratified sediments and from the deposits left by the superimposed streams, and they should include both the salt-rich fractions and those that are salt poor. Samples also would be desirable from post-Noachian sedimentary sequences that occur in local lows within the predominantly Noachian uplands, particularly where there is supplementary evidence that water was involved in their deposition. Samples also would be desired of layered deposits from more extensive low areas, such as Utopia within the northern basin, should any be identified. Such samples would indicate whether bodies of water had in fact ever occupied these areas and if so what kind of depositional regimes prevailed. As with the Noachian, if any hydrothermal deposits are identified, they would be of interest, and in the event that mineralogical evidence of substantial (cm+ - thick) young weathering profiles is found, they would be of high priority for sampling. Samples of Hesperian and lower Amazonian plains around the South Pole might provide clues about water activity and climate in middle Mars history. Water ice has played a significant role in the evolution of the landscape in the mid to high latitudes. In the fretted terrain, in particular, large fractions of ground ice are probably present near the surface. The ice is probably old, and might be of interest for its isotopic composition and presence of other volatiles.

Recent (<100 My) Mars history. The main geologic objectives of samples from this era would be first to determine if indeed there has been any recent activity at the surface involving liquid

water, and second to determine the effects of astronomical motions on the distribution of water and ice. Present day liquid water has been invoked to explain gullies, together with their associated bright streaks and dark streaks. The origin of both features is, however, controversial. Alternative suggestions for the gullies are that they formed by dry mass wasting or with liquid water but during a former period of high obliquity. The dark streaks have also been attributed to dry mass wasting. Samples of deposits at the ends of the gullies could resolve these issues and have broad biological and geological implications. The recent history of the redistribution of water as a result of astronomical perturbations may be recorded in the polar layered deposits (and perhaps further afield in near-surface regolith deposits at mid- to low-latitude). The sampling of polar deposits should include both light and dark bands at various stratigraphic levels. At both poles samples should also be taken of the stratigraphic units below the uppermost layered sequence.

Two major issues could confront the selection of samples that would lead to a better understanding of the history of water. The first would be our ability to confidently identify where the desired samples could be collected. The difficulty of identifying water-processed samples is illustrated by Gusev crater, where geologic evidence from orbital imaging strongly, but falsely, suggested that lake deposits might be accessible near the landing point. The second issue would be our ability to date the samples and so determine the sample's historical contexts. Dating the age of sedimentation, sedimentary processes and ices is difficult on Earth. It would be much more difficult on Mars where we would have far less supporting stratigraphic and chemical data. The types of samples listed below are narrowly directed toward understanding water-related processes, but their selection should be accompanied by a sampling program directed at dating the samples, and this might require a complementary suite of samples.

Sample types needed. Materials that water has altered either physically or chemically. Examples of key rocks include aqueous clastic and chemical sediments, and aqueously weathered soils, and cemented eolian features. Examples of key minerals desired in samples include phyllosilicates, sulfates, carbonates, SiO₂ minerals, other hydrous minerals, soluble salts (e.g., halides, nitrates, etc.) and minerals associated with hydrothermal activity.

Sample diversity needed. A suite of aqueous sediments in layered sequences should be taken from appropriately diverse stratigraphic horizons that would allow their depositional environments to be defined. A variety of sedimentary structures, the size, sorting and rounding of grains, the distribution of soluble minerals would all help understand the environment under which the sediments accumulated. Sequences of samples from soil profiles would define the processes and conditions of soil formation. Should hydrothermal deposit be discovered, sequences of samples along paleo-temperature, paleo-flow lines and/or paleo-redox hydrothermal gradients would help to define their environments of formation, including potentially the fluid compositions.

Physical condition (rock, pulverized rock, etc.). Intact rock samples such as chips and cores would be optimal because they best preserve any fluid inclusions or environmentally labile hydrated phases in addition to textural evidence of aqueous processes. Pulverized rock might be useful to identify relatively more stable hydrated phases if sample are not heated during collection and handling to the point where such phases would be degraded.

Contamination types and limits that affect this investigation. Water and any materials having exchangeable oxygen and hydrogen in spacecraft materials might affect the abundance and stable

isotopic composition of hydrated samples. Amounts that exceed the equivalent of 1000 ppm water in the samples might create serious levels of contamination. The stable isotopic composition of any exchangeable oxygen and hydrogen in spacecraft materials should be characterized.

Sample number and mass. The requirements for mineralogical context, the expected abundances of hydrous phases and the contamination concerns would call for individual sample sizes in the range 1 to 5 grams, especially for textural analyses. Note however, that all chemical and isotopic analyses likely could be performed with samples on the order of ~1 gram. The composition of host phases, together with the anticipated need to sample stratigraphic sequences (minimum 3-5 samples), soil profiles (minimum 3-5 samples) or geochemical gradients (minimum 3-5 samples) indicate that at least ten samples would be required to achieve this investigation.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Temperatures that exceed maximum Mars ambient temperatures at the site of collection are expected to alter any ices and also the most sensitive hydrated minerals. Partial pressures that are lower than those at minimum Mars ambient partial pressure would similarly cause degradation of these phases. The stability of hydrated sulfate minerals is also highly sensitive to relative humidity and control or, at the least, monitoring relative humidity would be a priority.

Maximum sample temperatures for sample integrity. Same as for Investigation A1: Keeping samples below maximum Mars ambient conditions would achieve 100 percent of the objective. Sample handling and storage temperatures that exceed 50°C almost certainly would seriously degrade some samples that contain polyhydrated phases. Samples of ice should be kept below temperatures where they sublime rapidly after acquisition and before storage in hermetically sealed containers. Storage containers should be hermetically sealed.

Impact of degradation on the investigation. Many sample types containing waters of hydration, hydroxyl groups or phyllosilicates would suffer alteration at elevated temperatures (see comments for Investigation A1). Elevated temperatures would alter phases perhaps to a point where the original hydrated phases could not be reconstructed. Loss of volatiles might fractionate the composition of those that remain to the point where original compositions could no longer be inferred. Elevated temperatures could decompose certain minerals and disrupt microscale diagnostic sedimentary textures. Accordingly, sealed containers would be a priority in order to preserve all components and maximize the possibility of “reconstructing” materials altered during sampling and transport to Earth.

Required/preferred sampling hardware. Rock and ice corers that would cause minimal heating during sampling. Sample handling that would heat the samples only minimally. Sample processing probably should be achieved outside the rover body to remain at or below Mars ambient conditions. The most thermally sensitive samples should be stored individually in hermetically sealed containers as quickly as possible but certainly within one sol of sampling.

Data needed for sample choice and in situ characterization. Image the rock outcrop or regolith sampling site to document their macroscale textures and any indications of their composition and origin. Perform spectroscopic (NIR or MIR) and elemental abundance measurements to guide selection of optimal samples.

Estimate of required mobility range. The need to land at a safe (flat) site would require mobility of several km in order to approach and sample key localities such as stratigraphic sequences, hydrothermal deposits, etc. and to perform observations of geological and environmental context.

Additional comments. Hydrated or water-containing samples tend to be sensitive to elevated temperatures or prolonged exposure to conditions where water vapor pressure is lower (or possibly higher) than in their original environments. These samples should be acquired and processed at or below maximum local ambient conditions. Sensitive samples should be stored in hermetically sealed containers within one sol of sampling. They would require similar confinement and storage conditions in the sample receiving facility on Earth.

A3. Investigation: Identify and characterize phases containing C, H, O, N, P and S, including minerals, ices, and gases, and the fluxes of these elements between phases.

Team leads: Pratt, Des Marais, Grady, Eigenbrode

Assessing the availability of biologically important elements and the phases in which they are contained would allow a greater assessment of both habitability and the potential for life to have arisen. Detailed investigations for carbon are the primary focus of Objective B and therefore will not be further expounded upon here. Nitrogen, phosphorous and sulfur are critical elements for life (as they are on Earth), and the phases containing these elements and fluxes of these elements may reflect biological processes and the availability of these elements for life. They are often intimately associated with carbon and their distribution is commonly controlled by water and oxidation states, so interpreting these elemental cycles in terms of C, H, and O is extremely valuable to understanding habitability. The redox chemistry of S is of interest because of its known role in some microbial metabolic strategies in terrestrial organisms and the abundance of sulfate on the surface of Mars.

The geochemical and biogeochemical cycles of carbon are intimately linked to five light elements that are the principal heteroatoms in biogenic and abiogenic organic matter. With the notable exceptions of graphitic or diamondoid carbon, heteroatoms serve to balance charge in materials with chains and/or rings of carbon as the backbone of the molecular structure. In biogenic organic matter, heteroatoms impart specific functionalities related to chemical reactivity or 3-dimensional shape. Heteroatoms are extracted from the surrounding environment during growth and are released back to the surrounding environment during decomposition following reaction pathways that often involve substantial kinetic isotope effects. Consequently, changes in elemental ratios or stable isotopic compositions of gases, liquids, and minerals are important lines of evidence for inferring the presence of extant or extinct life. Sedimentary materials deposited or precipitated in the presence of liquid water would be the most important target rocks for investigating heteroatomic links in the carbon cycle on Mars. Hydrothermal or mesothermal mineral deposits along fracture or gully flow paths for geofluids would be additional priority targets for sampling. Fresh rather than weathered samples would be a priority given the reactivity and valence variability of carbon, nitrogen, and sulfur.

Due to the close links among these elements, this investigation substantially overlaps Goal 1, B1: Determine the distribution and composition of organic carbon on Mars. It is also linked to Goal 1, A4: Determine the array of potential energy sources available on Mars to sustain biological

processes, because many of these elements are important in biological metabolic cycles. The investigation requirements described here are exactly the same as those in Goal 1, B3: Characterize links between C and H, O, N, P, and S because the sample needs would be identical.

Sample types needed. Rocks cores or rock fragments would be the types of samples needed to study minerals that are sensitive indicators of links between C and H, O, N, P, and S. Direct evidence of carbon cycling could be found in sedimentary organic matter, minerals containing hydrocarbon-bearing fluid inclusions, minerals containing sorbed organic acids, and methane-bearing clays or zeolites. Hydrogen and oxygen are common in many minerals and aqueous fluids, so links to the carbon cycle would be established primarily through stable isotopic compositions of sedimentary deposits containing phyllosilicates, carbonates, and hydrated evaporates. Oxidized and reduced forms of nitrogen are relatively uncommon in minerals so samples containing nitrates, ammonium minerals, and ammonia-bearing clay or zeolite minerals would be high priority targets for sampling. Phosphate minerals can incorporate Fe(II), Fe(III), Mn(II), and Mn(IV), thereby providing evidence of changes in redox, commonly associated with decomposition of organic matter. Similarly, carbonates can serve as sensitive indicators of reducing aqueous conditions by incorporation and preservation of Fe(II) and Mn(IV). Evidence of sulfur associated with carbon cycling can be found in sulfate minerals containing Fe(II) or Fe(III), elemental sulfur, metallic disulfides, and metallic monosulfides.

Sample diversity needed. Scientific objectives would be diversity driven and necessitate sedimentary or hydrothermal/mesothermal rocks units and evidence of geological diversity within rover range. A suite of ~5 samples would provide a good estimate of initial diversity.

Physical condition (rock, pulverized rock, etc.). Fresh rock collected by impact fracturing or coring would be required to maintain sample integrity.

Contamination types and limits that affect this investigation. Contamination by refined hydrocarbons (waxes, lubricants, and greases), soft plastics, and solid rocket fuels (nitrogen, carbon, and sulfur constituents) would be highly problematic even at low ppm or high ppb levels. Specific levels that would be required are similar to those listed in Goal 1, B1, "Determine the distribution and composition of organic carbon on Mars" due to the similar nature of required samples.

Sample number and mass. Sample number depending on variation in rock type and the currently unknown concentrations of CHNOP and S. Sample mass in the 1-2 gm range with a few samples in the 5-10 g range to allow for molecular characterization of trace-level organic constituents if they are abundant enough. Specific constraints on abundances are described in Goal 1, B1: Determine the distribution and composition of organic carbon on Mars. Sample requirements would be the same for this investigation

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Samples for this investigation would be highly vulnerable to degradation associated with oxidation and or hydration due to reactive character of potential electron donors (non-aromatic organic matter and minerals containing reduced metals). Specific constraints for organic compounds are listed in Goal 1, B1: Determine the distribution and composition of organic carbon on Mars. For minerals containing CHNOP and S, samples are less vulnerable to degradation, but volatile loss could significantly changes trace component concentrations.

Maximum sample temperatures for sample integrity. Storage and transportation conditions would need to remain at or below maximum ambient surface temperature for surface samples and at or below collection temperature for subsurface samples. See specific constraints for organic compounds under Goal 1, B1: “Determine the distribution and composition of organic carbon on Mars.” For minerals containing these elements, little degradation is likely at 50°C for less than a few hours in the absence of hydrous phases. However, oxidative processes are likely present if water is released during heating, which would significantly damage sample integrity.

Impact of degradation on the investigation. See specific effects for organic compounds under Goal 1, B1: Determine the distribution and composition of organic carbon on Mars. Redox reactions catalyzed by water would substantially reduce the value of samples due to changes in bonding of these elements.

Required/preferred sampling hardware. An impact tool or corer on a rover arm that could extend 10 cm or more away from the rover footprint would be preferred.

Data needed for sample choice and in situ characterization. Millimeter-scale imaging, mineralogical information, and elemental composition would be required for sample collection.

Estimate of required mobility range. Hundreds of meters to a few kilometers would be needed to obtain sample diversity.

Additional comments. All samples would need to be individual package in gas-tight glassy containers. Temperatures would need to be maintained well below the freezing point of concentrated sulfate brines. Head-space gas could be Martian atmosphere or an inert gas and oxidant-resistant seals would be required.

A4. Investigation: Determine the array of potential energy sources available on Mars to sustain biological processes.

Team leads: Pratt, Neilson

This investigation would allow identification of the potential of Mars to have harbored or continue to harbor life. Biological systems require energy. Therefore, measurement of the availability of potential energy sources would be a critical component of habitability, and understanding how life might use them is a critical component of designing scientifically robust life detection experiments. Sources of energy that should be measured may include chemical redox, pH gradients, geothermal heat, radioactivity, incident radiation (sunlight), and atmospheric processes.

Energy for life can come from sunlight or chemical disequilibrium. Solid, liquid, and gaseous species on Mars provide chemical energy that could be used by life. Thus, the characterization of oxidation contrasts and the energy available for various potential biological reactions would provide a context in which to understand potential energetically useful metabolisms. Such analyses would be greatly enhanced by the return of virtually any sample of rock, regolith, regolith gas, atmospheric gas, or ground ice obtained from Mars would enhance our understanding of energy sources.

The wide range of samples that would be useful for this investigation means that sample requirements would overlap those of many other investigations. In addition, much of the characterization could be accomplished *in situ*. Thus, this investigation would place few

constraints on specific samples, and it should be viewed as a supplementary benefit for sample return rather than a driving influence on landing site or sample characteristics.

Sample types needed. Any sample category would be useful, and the following sections are divided into these groupings: 1) Sedimentary rocks; 2) Hydrothermal rocks; 3) Low temperature weathered rocks; 4) Igneous rocks; 5) Regolith; 6) Dust; 7) Ice; and 8) Atmospheric gases.

Sample diversity needed. Suites of rocks with contrasting oxidation states would be required for types 1, 2, 3, 4, and 5. Particular attention should be paid to variations in rock units likely to contain Fe- and Mn-bearing minerals, metallic monosulfide or disulfides, and organic carbon. These phases often have multiple oxidation states and have the potential to serve as electron acceptors or donors in metabolic pathways.

Regolith samples (5) from multiple sites and at multiple depths (e.g. 2, 5, and 10 cm below the surface) would be needed to assess the influence of bedrock on chemical composition and horizonation of regolith. This would provide information on oxidation gradients that could be used by biological processes.

Single samples of dust (6) and atmospheric gases (8) would be sufficient to address this investigation. However, multiple samples of pore gases within regolith would be necessary to provide constraints on energy available in volatiles within the regolith.

Stratigraphically constrained samples of ground ice (including water ice, CO₂ ice, and clathrates of CO₂ and/or CH₄) would be needed to assess the current upward flux of volatiles as well as the potential for periods of high obliquity to impact the availability of energy from release of previously sequestered volatiles in ices and hydrated minerals.

Physical condition (rock, pulverized rock, etc.) Intact samples of rock would be most useful, although oxidation state variations could be characterized in pulverized rock. Gas samples must be collected separate from other samples, as must ice samples.

Contamination types and limits that affect this investigation. Rock and regolith samples would have low sensitivity to parts-per-million level contamination from refined hydrocarbon lubricants or plastics, moderate sensitivity to parts-per-million level contamination from industrial metals, and low sensitivity to parts-per-million level contamination from industrial glasses or enamels. Ice samples would have high sensitivity to contamination from hydrocarbons and metals due to the possibility of inducing phase changes or having diffusion of contaminants in water films at grain boundaries.

Sample number and mass. Suites of ~5 samples of each type with a minimum mass of 2-3 grams are would be necessary for this investigation.

Concentration of methane, carbon dioxide, and water vapor as well as isotopic composition of hydrogen in methane and water vapor and isotopic composition of carbon in methane and carbon dioxide from regolith gas would be important scientific objectives for assessing available energy. Twenty milliliter gas samples containing 30 nanomol of water vapor could be analyzed for the hydrogen isotopic composition of hydrogen using commercial IR instrumentation. A regolith gas sample containing about 50 micromol of methane or carbon dioxide would be needed for duplicate determinations of the carbon isotopic compositions in a return sample using routine gas source mass spectrometry. Assuming 1 ppt methane at 0.01 atmosphere, each return gas sample would need to be about 5 ml in volume. Development of more precise analytical techniques would allow smaller gas samples.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Due to interest in potential electron donors for metabolism, fresh-rock samples collected as cores or chips would need to be protected from exposure to atmospheric oxidants and to moisture. Volatile loss would be a particular problem for hydrated minerals and ices. Temperature sensitivity would be a serious problem if hydrated minerals decompose or dehydrate. Although alteration temperatures are mineral specific, keeping the sample at or below maximum ambient temperature at the sample site would be the best way to ensure the integrity of hydrated minerals. Ice samples would require maintaining samples at or below the temperature of the ice at the time of sampling.

Maximum sample temperatures for sample integrity. For non-hydrous rock and regolith samples, a maximum temperature of 50°C for several hours would not impair this investigation for inorganic components. Volatile organic components could be lost and would begin to react at temperatures and pressures above ambient Martian conditions, and disequilibrium gas components, such as CH₄, may also react at temperatures of 50°C. Temperatures of 10°C would be much preferable. Hydrous minerals should be maintained at ambient martian conditions to maintain oxidative disequilibrium. Ices, if returned must be maintained at -10°C or colder temperatures to limit redox reactions and volatile loss during return to earth.

Impact of degradation effect on the investigation. Degradation of gases, ices, and hydrated minerals would significantly reduce the scientific value to below justification for return samples because the reconstruction of initial redox conditions are probably not possible. Partial oxidation and hydration of rock and regolith samples would still allow for significant scientific study of material below the zone of alteration. Anhydrous samples are unlikely to be subjected to significant oxidative equilibration, unless they are organic-rich.

Required/preferred sampling hardware. Sampling hardware needs would be highly variable depending on type of sample. A method for collecting intact, fresh rock samples would be highly desirable. Stratigraphically preserved, solid ice samples would be needed. Gas samples might need concentration to sample a sufficient number of moles for isotopic analyses.

Data needed for sample choice and in situ characterization. Visual images with millimeter-scale resolution and spectral data on mineral and bulk elemental composition for rock and regolith samples would be needed to identify the most appropriate samples. Gas analysis capable of detecting methane and water vapor concentrations in regolith gas samples and the composition of volatiles from ground ice would significantly improve the quality of gas samples.

Estimate of required mobility range. A minimum mobility of 100's of meters to a kilometer away from landing contamination would be essential for clean samples of trace volatiles. Access to multiple rock units would be required for collection of a diverse suite of samples to characterize variability in oxidation states.

Additional comments. Both biogenic and abiogenic organic matter in gaseous, liquid, and solid states are significant potential energy sources for life. Although the concentration of organic constituents at or near the surface may be low, a few larger rock samples (5 to 10 g) should be collected in order to fully inventory the concentration and composition of organic matter.

B. Objective: Characterize Carbon Cycling in its Geochemical Context

B1. Investigation: Determine the distribution and composition of organic carbon on Mars.

Team leads: *Eigenbrode, Benner, Conrad, Glavin, Steele*

The spatial distribution and composition of organic carbon have not been characterized, but are instrumental in understanding the biological potential of Mars. (Methane and other simple reduced carbon molecules are included as “organic carbon” in this context.) Abiotic synthesis of organics, delivery of organics to Mars via meteorites, and possible biological production of organics must all be evaluated in the context of carbon cycling on Mars. Characterizing the molecular and isotopic composition of organic carbon is essential for determining the origin of the organics shown in Table 2, which includes the types of organic materials that need to be detected and deconvolved from each other. Investigations would require sufficient spacecraft cleaning and verification to avoid likelihood of contamination, in addition to careful planning of specific methods to identify and exclude forward contamination at the experiment level. Example measurements include analysis of the concentration and isotopic composition of organic carbon, characterization of the molecular structure of organic carbon, or identifying and monitoring reduced carbon (e.g., methane) fluxes.

Organic materials are a key component of a biological carbon cycle, and they may play an important role in the carbon cycle of a planet without life. They have a variety of sources including primary biologic, subsurface abiogenic (i.e. from serpentinization), and meteoritic origins, in addition to secondary diagenetic derivatives of the former. A suite of organics in a single sample could be derived from more than one of these sources. An understanding of the geological and atmospheric processes that influence organic carbon distribution, preservation, and alteration would assist in the identification of organic carbon and, once detected, provide contextual support for understanding organic carbon distribution and composition.

The investigation of the distribution of carbon on Mars could be approached on several levels, which could be viewed as interlocking investigations. Different approaches would be suitable for specific sub-investigations, such as:

Sub-investigation A. Stability and spatial distribution of exogenous organic carbon (meteoritically delivered)

For this question, we must consider the distribution on a planetary scale as well as on smaller spatial scales associated with crater impacts, sedimentary structures associated with aqueous alteration such as down-cut channels indicative of fluvial transport, and volcanic lava flows. In addition to lateral distribution and association with sedimentary structures or other morphological relationships, we would also want to understand distribution with depth, not only as a function of gardening, but also as a function of the stability of the meteoritically-predicted organic molecules while under attack by radiation and putative chemical oxidant(s). Therefore, assessment of exogenous organic carbon distribution would entail several spatially distributed sets of measurements, potentially associated with a variety of specific geologic environments and temporal ranges and each including a depth profile. Rover-accessible geological diversity within traversible rover range would support this approach; however, measurements to assess latitudinal variations would require multiple missions.

Sub-investigation B. Distribution of indigenously produced organic carbon

There could be several types of indigenous organic carbon on Mars: (1) abiotically produced (either by deep alteration of igneous rock or sedimentary alteration subsequently, or by prebiotic synthesis in a reducing or mildly reducing environments) and (2) potentially biogenic organic carbon. The optimal geologic settings for finding these records may differ. The abiologically produced organic C associated with mafic-rock weathering might be more likely within basalts that were hydrothermally altered. The possible biogenic or biologically affected organic carbon might be better detected in aqueous deposited sediments as in a delta and/or lacustrine setting or spring.

Because we want to know the same distributions for sub-investigations A and B, a diversity of geologic samples would be required. That being said, to answer the really big question: What is the global cycling of carbon on Mars, we need to understand the different organic carbon sources, fluxes and sinks, as well as the partitioning of carbon between organic and inorganic phases, including gases. Thus, carbon isotope measurements of CO₂ released from carbonate (if we find any), the atmosphere, and any organic material would be VERY important in order to understand the impact of a potential biosphere on metabolic isotopic fractionation, the source of any organic carbon detected (e.g., indigenous versus exogenous).

The requirements and strategies for addressing this investigation largely overlap with other goal 1 investigations (A3-4, B3-4, and C1). Moreover, addressing other investigations (Goal 1: B2-3, C1-4, and others) would provide complementary support for this investigation and would be necessary to build an understanding of carbon cycling on Mars.

Sample types needed. Rocks samples containing or in association with reduced carbon should be given the highest priority. These might include sedimentary rocks, mafic basalt and peridotite, regolith, and mineral precipitates from aqueous solutions. Geologically diverse samples that include samples with reduced minerals also would be a high priority. Samples containing halogenated salts, precipitated cements, and phyllosilicates, which may assist in organic preservation should be considered within geological context of potential sampling sites. Selecting samples that are more likely to contain organic carbon and to preserve organics during the process of acquisition to analysis would improve the likelihood of success in detecting, characterizing, and structurally inspecting organic carbon.

Samples most likely to have been preserved reduced carbon would have been shielded from the effects of ionizing radiation (galactic and solar) on the Martian surface from the time of deposition to sample acquisition. Aquatic basins and geological materials contribute to this shielding. Quick removal from the surface condition (e.g., burial or cementation) would likely enhance chances of organic carbon preservation. Sub-investigations should include sample collection from various depths in the subsurface or alternatively from geological materials that have been recently exhumed or eroded, exposing radiation-shielded terrain.

Sample diversity needed. A diverse sample suite including samples containing reduced carbon would be desired. Sample suites should include lithologic, spatial, and/or temporal diversity from geologically related materials over spatial scales of 2 m or more (with respect to depth, geomorphology or stratigraphy to the lateral range of a rover).

Physical condition (rock, pulverized rock, etc.). Consolidated sediments, unweathered and weathered rock fragments, or core material would be required by this investigation and depend on the specific approach. Rocks pulverized by a drill bit or unconsolidated sediments have high surface area making them more susceptible to alteration and contamination by rover-hosted and

terrestrial organics; they would not be appropriate for determining microscopic textural, chemical and isotopic spatial relationship using Earth-based analytical tools, which would be an important driver for sample return.

Contamination types and limits that affect this investigation. Forward contamination by organic polymers, lubricants, biomolecules, dust and other compounds containing carbon could critically affect this investigation and must be minimized and monitored. Some Earth-based instrumentation that would be used on returned samples (e.g. ToF-SIM) is sensitive enough to detect organics adsorbed from the air after seconds of exposure.

Flight hardware should be decontaminated for organics as much as possible in addition to biological load as defined by current planetary protection requirements. A comprehensive organic molecular inventory for the mission would be necessary to establish chemical relationships and establish a resource for cross-checking for Earth-contaminants. Sets of witness plates (e.g., silica wafers, molecular absorbents) should be employed to measure contamination during the mission. In particular, witness plates would record contaminants derived from the rocket descent and other landing effects, such as bag inflation. They would collect evidence of the organic “noise” necessary for deciphering signatures from samples. Separate, additional sets of witness plates should be used to record contamination during curation and processing upon return, where individual witness plates would serve different analytical applications. Every effort should be made to minimize sample handling. All tools and containment vessels should be made of metal, glass, or ceramic decontaminated for organics. Every effort must be made to avoid exposure to solid plastics (including fluorinated polymers if possible) and plasticizers leached into liquids and gases.

Samples should be transferred to storage containers quickly, preferably autonomously within minutes but no longer than one communication cycle. Samples should be stored in sealed aluminum, electropolished stainless steel, or similar low-organic containers. See below for additional sampling requirements.

Sample number and mass. It is difficult to estimate how much sample material would be necessary to address this investigation in the absence of detected organics on Mars. Assuming only exogenous reduced carbon is present and the mass influx of meteorites and IDPs is 3×10^9 to 6×10^{10} g/yr to the surface of Mars (Flynn, G. J. and McKay, D. S., 1990, J. Geophys. Res. 95, 14497-14509), meteoritic material could account for between 2 to 29 wt. % of total Martian surface soil. Applying a conservative estimate of ~1 wt. % of meteoritic material in the soil, a 1 g sample of Martian regolith would have 10 mg of IDP material containing 1 mg of carbon (10 wt.% carbon in IDPs). Thus, a conservative estimate of exogeneous carbon would suggest parts per thousand concentrations of reduced carbon in Martian soil if none of it decays. However, this estimate is inconsistent with a negative result for ppb concentrations of organics in the soil by Viking, suggesting that organics are being oxidized to CO₂, the IDP influx estimates are in error, and/or organic matter from IDPs is diluted by transported sediments. In the absence of additional constraints on organic concentrations and organic composition in rocks and regolith, we must assume that organic carbon is present in trace quantities that may challenge the detection limits of many analytical instruments. Thus, our recommendation would be to collect as much sample as possible. One to ten grams of sample are recommended for characterization, spatial distribution, isotopic and molecular composition using a range of analytical tools and assuming total levels of organics in the martian regolith of 10-100 ppb.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). The structural components in organic matter will continually react until metastability is reached. Reactions include stereochemical changes, structural rearrangements, bond cleavage and reaction with other chemical species (e.g., water, oxidants, halogens, metals, and other organics). Changes in temperature, pressure, and redox conditions promote alteration and increases in temperature and pressure can lead to volatile loss. Mineral phases may also undergo reconstructive phase transformations, changing microscale geochemical conditions and influencing organic molecule stability and inclusion chemistry. Organic biosignatures of both isotopic and molecular nature are particularly vulnerable to alteration and loss. These processes occur naturally in most environments; however, post-acquisition conditions could obscure or destroy the organic structures present at the time of acquisition.

Maximum sample temperatures for sample integrity. Due to the lower atmospheric pressure on Mars, volatiles could be lost from samples by moderate heating above Martian surface conditions. They would need to be trapped and contained. Heating followed by cooling could lead to migration of low molecular weight organics from the interior of the sample to outside the sample where the migrated molecules could condense on sample and container surfaces. Whereas refractory organic matter such as ancient organics can withstand temperatures of 120-200°C, more labile organics containing functional groups, which are common of biomolecules, will begin to degrade at temperatures above 50°C, although significant alteration of amino acids does not begin until 250°C at Martian pressure. Temperatures below 50°C would be highly desirable, with temperatures below 10°C substantially improving sample integrity.

Impact of degradation effect on the investigation. Degradation of organics after sampling would significantly reduce the quality of samples and limit results of this investigation if less refractory organics are present. However, if any organics are present, some of the more stable phases are likely to be preserved, providing substantially more information than is currently available about the organic inventory on Mars. Much more characterization of these organics could be accomplished in returned samples than is possible from *in situ* analyses.

Required/preferred sampling hardware. A coring device or other method for providing intact rock samples would be preferred for sampling materials that are not strongly oxidized in the surface environments. Alternatively, an impact chisel or drill might suffice for specific sub-investigations.

Data needed for sample choice and in situ characterization. Geological context at regional to microscopic scales could provide key insight into the sources, specific processes of formation of organics if they formed *in situ* (e.g., catalytic mineralogical assemblages for abiogenic carbon), patterns indicative of ancient and extant ecosystems (e.g., stratigraphic, geomorphic, and geochemical facies in association with organic composition), and preservation and alteration mechanisms that influenced any organic compounds. This geological and geochemical context is critical for understanding the distribution and factors that influence organic compositions or a paucity of organics. Panoramic stereo images from the acquisition platform linked to high-resolution remote sensing images should be used to assess the regional and local morphological, structural, and stratigraphic geology and macroscale textures. In addition, *in situ* characterization of mineralogical assemblages and associations would be necessary to guide sample selection. In particular, an *in situ* survey of the local geochemistry/mineralogy and presence of reduced chemical species would be necessary for sample selection and establishing geological context.

Although these methods might detect ppm reduced carbon, an independent test for sub-ppb reduced carbon (i.e., below Viking detection limits) would be desired.

For this investigation, more contextual information would improve our chances of selecting the optimal samples for return to Earth. *In situ* detection of reduced carbon would be strongly desired for sample selection; however, a positive reduced-carbon observation would not be required in the absence of organic detections by missions prior to sample return. Sample sets that include samples with detectable reduced carbon would have the greatest utility in assessing sources and processes influencing organic composition. However, samples lacking reduced carbon might be useful for understanding factors influencing organic carbon preservation, alteration, and loss.

Estimate of required mobility range. Sufficient mobility to obtain a diversity of samples and contextual data would be required for this investigation.

Additional Comments. Samples with a very low surface area would be less likely to be compromised by alteration reactions and contamination. Drill core or rock fragments would be preferable and allow for a greater variety of analyses on Earth (including spatially resolved spectroscopic analyses), as well as contributing to optimal preservation conditions and protection from contamination. They would also maintain *in situ* geochemical relationships, which provide key contextual data for understanding the processes influencing organic carbon distribution and composition.

Preservation of organics from recent biological activity would require substantially more restrictive sample return conditions than organics from abiotic processes or preserved from ancient life because they are more reactive and volatile. (Abiotic and old biotic organics have, presumably, already reacted significantly with their environment, eliminating many of the compounds of greatest interest in recent communities.) If evidence for recent biological activity is obtained prior to sample return, every effort to preserve these less stable organics should be made. To minimize alteration to organic structures, samples should ideally be maintained under the following conditions:

- At pressure conditions within the bounds of ambient conditions experienced on Mars for the sample to preserve volatiles
- At temperatures not to exceed the upper bound of ambient Mars conditions for the sample (or 50C) for any longer than absolutely necessary, and ideally at -20°C for short-term storage to preserve reactive functional groups such as double bonds in carboxylic acids, -80°C for long-term storage (>1 yr) to preserve nucleobases sequences if present, and at 4°C during analytical use.
- Under inert conditions to minimize reactions such as oxidation and reduction, and maintain ambient pH conditions.
- Under as much protection as possible from cosmic radiation exposure until returned to Earth in order to minimize radiation induced bond cleavage and subsequent reactions.

Recommendations for sample validation and curation include:

- Surfaces and gases of the sample container should be examined for carbon in their initial returned state.

- Intact samples should have context imaging on the ~100 micrometer scale prior to storage.
- Organic cleanliness must be verifiable to the detection limits of instrumentation prior to launch for *in situ* instrumentation and during curation and analysis upon return.
- Introduction of contaminants and alteration of sample chemistry must be carefully considered before physical sample alteration (crushing, slicing, etc.) in order to avoid compromising the sample for other investigations.

B2. Investigation: Characterize the distribution and composition of inorganic carbon reservoirs on Mars through time.

Team leads: Des Marais, Sumner, Grady, Westall,

Transformations of carbon between inorganic and organic carbon reservoirs are a characteristic of life. Evaluating carbon reservoirs and the fluxes among them is critical to understanding both the modern and geological evolution of carbon availability, and the inorganic carbon reservoirs are an important link in the cycle. The distribution of these reservoirs can also reveal critical habitability information because they can record climate records. Potential measurements include continued searching for carbonate minerals from orbit, *in situ*, and in returned samples, characterizing CO₂ fluxes on various time scales globally and locally, and measuring the isotopic composition of any inorganic reservoir.

Carbonates sequester more than 80% of Earth's total crustal inventory of carbon, and their analysis conveys critical paleoenvironmental information. Carbonates would be key exploration targets on Mars for the same reasons they are important on Earth. However, recent surface environments on Mars are inimical to carbonates due to their destruction by impacts, radiation, and acidic weathering reactions. Carbonate-rich bedded deposits analogous to continental platform deposits on Earth have not been identified on Mars, and they might be very rare or absent either because they did not form or because of preservational challenges. In contrast, a substantial fraction of the Martian crustal carbon inventory might reside as carbonates sequestered within subsurface fractures. Carbonate inventories could be characterized either by retrieving samples wherein carbonates have been protected from degradation or by identifying minerals and lithologies that contain phases that replaced former carbonates.

In the following, we assume that the only carbonate detected prior to sample return is within dust or in trace quantities in fractures in rocks.

Sample types needed. Detection of trace Mg-carbonate has been reported in Martian dust. Thus, a sample of dust would be required.

Intact samples of rocks that might contain carbonate minerals would be needed to evaluate the presence or absence of carbonates, and to evaluate geochemical spatial heterogeneity of carbonate minerals if present. Such rock samples could include sedimentary rocks, hydrothermal rocks, and altered igneous rocks.

Sample diversity needed. Only one sample of dust would be required because the Mg-carbonate appears globally distributed. Contamination by a small component of regolith would be acceptable.

Should aqueous sediments in layered sequences containing carbonate be detected, samples should be taken from appropriate stratigraphic horizons where depositional environments to be characterized to allow investigation of processes leading to the sedimentary accumulation of carbonate. Hydrothermal and altered igneous rocks might harbor carbonates in cracks, voids or alteration zones. Should hydrothermal deposit be discovered, sequences of samples along paleo-temperature, paleo-flow lines and/or paleo-redox hydrothermal gradients would help to define their environments of formation, including potentially their carbonate contents. Fractures, voids, and surface alteration features of altered rocks should each be sampled.

Physical condition (rock, pulverized rock, etc.). One dust sample would be required for characterization of magnesium carbonate in dust.

Intact rock samples would be required for characterizing the spatial relationships within carbonates and between carbonates and host rocks if carbonate is present as a phase within other rock types. Pulverized rock might be useful for chemical analyses of any carbonate phases but would not retain the highly valuable spatial information that sheds light on processes leading to the formation of carbonate.

Contamination types and limits that affect this investigation. Samples should not be exposed to acidic conditions, CO₂ or moisture that might alter the chemical and isotopic composition of any trace carbonate phases. Storage containers should be hermetically sealed to limit contamination.

Sample number and mass. One gram of dust with 1-3% Mg-carbonate would be sufficient to characterize the elemental and isotopic composition of the carbonate known to exist on Mars. The requirements for mineralogical context in rock chips and cores and the expected (relatively minor) abundances of carbonates calls for individual sample sizes in the range 1 to 5 grams. Chemical and isotopic analyses likely could be performed with samples <1gram.

The absence of carbonate detections in rocks on Mars makes estimating sample number necessary for this investigation difficult. However, an initial documentation of the presence or absence of carbonate could be performed by sampling diverse phases within geological contexts where carbonates might be expected. Stratigraphic sequences or altered bedrock should be sampled (minimum 3-5 samples), as should soil profiles (minimum 3-5 samples) and geochemical gradients (minimum 3-5 samples), depending on the landing site. Thus, at least ten samples would be required to initially evaluate the presence or absence of carbonate in the landing area within the context of this investigation. If carbonates are present, they could be characterized within the 1 to 5 gram sample sizes needed to evaluate the presence of carbonates.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Temperatures that exceed maximum Mars ambient temperatures at the site of collection might alter some hydrous bicarbonate and carbonate minerals that could be present. For example, sodium bicarbonate decomposes at ~50°C and ikite decomposes at 7°C.

Maximum sample temperatures for sample integrity. Keeping samples below maximum Mars ambient conditions would achieve 100% of the objective. Sample handling and storage temperatures that exceed 50°C would degrade hydrous bicarbonates. Anhydrous carbonates are stable at least to 100°C or above, but finely disseminated carbonates might begin to exchange isotopically with water vapor above 50°C.

Impact of degradation effect on the investigation. Elevated temperatures could decompose certain minerals and disrupt microscale diagnostic sedimentary textures. Decomposition of bicarbonates could compromise reactive geochemistry within the sample. Carbonates might begin to exchange isotopically with water, etc. above 50°C. Carbonates might begin to react with other phases above 100°C. Sealed containers would be a priority in order to preserve all components and maximize the possibility of “reconstructing” any materials altered during sampling and transport to Earth.

Required/preferred sampling hardware. Rock corers that achieve minimal heating during sampling would be the preferred sampling technique for intact rock samples. Dust collection hardware should include non-magnetic grains if present.

Data needed for sample choice and in situ characterization. Image the rock outcrop or regolith sampling site to document macroscale textures and any indications of their composition and origin. Mineralogical and elemental abundance measurements would guide selection of optimal samples, particularly if carbonates are identified.

Estimate of required mobility range. The need to land at a safe (flat) site would require mobility of several km in order to approach and sample key localities such as stratigraphic sequences, hydrothermal deposits, etc. and to perform observations to acquire geological and environmental context.

B3. Investigation: Characterize links between C and H, O, N, P, and S

Team leads: Pratt, Des Marais, Grady, Eigenbrode

The carbon cycle is intimately linked to H, O, N, P, and S, particularly in the presence of life. Identifying connections among the geological cycles of these elements would substantially aid interpretations of the carbon cycle and might provide indicators that could be used to interpret biological potential. Potential measurements include mineralogical characterization of samples containing C, N, P, or S, isotopic and oxidation state characterization of S-containing phases, and identification of reactions involving any of these elements.

In the current absence of detection of organics, this investigation currently entirely overlaps Goal 1, A3 Identify and characterize phases containing C, H, O, N, P and S, including minerals, ices, and gases, and the fluxes of these elements between phases. Please see sample requirements listed under Goal 1, A3.

B4. Investigation: Preservation of reduced compounds on the near-surface through time

NOTE FROM REVIEWER: I don't know what to do with this section. As originally conceived, the investigation was a place-marker for understanding the oxidant in the regolith that may have removed the organic carbon; thus, its presence in Objective B. However, as worded and interpreted by the ND-SAG subgroup, it is much broader. I find it so broad that it seems nearly impossible to fit into the context. I would be more comfortable restricting it to the surface oxidant, but I do not want to unilaterally discard the other sample considerations. Please advise.

Team leads: Westall, Benner, Steele, Zent

The surface of Mars is oxidizing, but the composition and properties of the responsible oxidant(s) are unknown. Characterizing the reactivity of the near surface of Mars, including atmospheric (e.g., electrical discharges) and radiation processes as well as chemical processes with depth in the regolith¹ and within weathered rocks would be critical to interpreting the paucity or possible absence of organic carbon on the surface of Mars. Understanding the oxidation chemistry and the processes controlling its variations would aid in predicting subsurface habitability if no organics are found on the surface. Potential measurements include identifying species and concentrations of oxidants, characterizing the processes forming and destroying them, and characterizing concentrations and fluxes of redox sensitive gases in the lower atmosphere.

Aaron Zent's comments about the "Viking Mars Oxidant:" Oxidation: It is very unlikely that the species that were responsible for either the absence of organics in the Viking samples, or their unusual chemical behavior in the Viking biology experiments, could be sampled *in situ* and returned to Earth without significant re-equilibration once removed from the Martian surface environment. The key requirement for preserving the chemical nature of the soil surfaces to the extent possible would be to keep the sample at low temperature, and to control the relative humidity such that the chemical activity of surface H₂O does not exceed its nominal value at the sampling site. This might be prohibitive, and any attempt to rigorously control the atmospheric ambient is likely to be unsuccessful, based on the lunar experience with fine-grained samples. It would be far more important to maintain the sample at Mars-ambient temperature, or ideally colder.

I would like also to weigh in on the subject surficial interactions between regolith particles and the atmosphere. I would again argue that it is very unlikely that the surface state of the regolith particles could be maintained in their original condition. Rather, I would again argue for maintaining the samples at low temperatures in order to prevent any surface alteration due to high H₂O activity. In addition, I would argue that it would be key to acquire samples from more than one depth.

I infer from the proposed measurements described by McLennan and Aharonson that there would be limitations on the depth-sampling capabilities of the nominal sample-return lander. Nonetheless, I would argue that depth-resolved samples capable of capturing any vertical inhomogeneity observed in imagery would be key. It would be potentially disastrous to scoop up a few cubic centimeters of surface material and then extrapolate that to the entire regolith (which everybody will do) if we could discriminate inhomogeneity in the near-surface regolith. Therefore, a key recommendation I would make would involve vertically resolved sampling of the regolith.

1. Are samples of specific character, geologic setting, or landing site) required to answer this question?

To test the preservation of reduced compounds in the near surface through time, we would need to select a variety of samples that include typical surface material, such as weathered basalt, sedimentary materials (relatively friable sulphate-rich sediments, sands derived from weathered basalt), as well as atypical materials, for instance any identified hydrothermal deposits (for

instance silica). The fresh basalt (if available) would act as a control sample as it would contain magmatic carbon.

Surface materials in the regolith appear to be to a greater or lesser extent altered by oxidation processes and the effects of concentrated acidic brines over long periods of geological time. Such materials would represent an “end-member” sample of martian material, potentially containing carbon, that has been significantly altered (implying also alteration of the carbon) probably in succeeding episodes.

We already know that volatile organics are readily lost from most surface materials on Mars but certain natural materials, such as silica in the form of chert (amorphous, hydrated SiO₂) is particularly impervious and it is possible that surface silica, if found, could contain a variety of organic components including volatiles, especially in the younger rocks.

Preservation through time – Comparison with terrestrial organics through time suggests that there will be a gradual loss of functional groups with increasing age of the sample, simply because of time-dependent degradation (like the racemisation of chiral molecules). Therefore, even if we could identify ancient silica, and, although it would contain “hermetically-sealed” organics (of abiogenic and/or biogenic origin), the latter would probably be represented by PAHs (mostly alkanes).

1.1. Sample types needed (in order of priority based on likelihood of preserving carbon in an unaltered a form as possible)

- Volcanic water-lain sediments that have not seen aqueous alteration since they formed and therefore have a pristine carbon signal (do they exist on Mars?)
- Hydrothermal deposits -
 - silica
 - carbonates?? (very leaky)
 - Fe minerals
- Volcanics that were extruded under water and have an alteration rind (do they exist)
- Evaporites (very leaky)
- Volcanic sediments that have been obviously processed by water and contain aqueously-formed alteration products
- Volcanic rocks as fresh as possible
- Weathered basalts

We would need these samples from both the surface and the near-surface. We would need to get below the zone of oxidation which would be different depending on whether we would be dealing with rock outcrop, rocks of different composition and texture (porosity), or regolith. With outcrop perhaps even a few cm or less would be sufficient in an impervious rock (like chert) but deeply weathered basalt or friable basaltic sediments probably would need to be sampled at a greater depth (decimetres to 1 m? This would need to be modelled).

1.2. Sample diversity needed

See above

1.3. Physical condition (rock, pulverized rock, etc.)

- Any rock samples need to be integral because the interior mineral matrix will protect any organics from eventual loss or contamination.

- Friable rocks are likely to disintegrate during transport.
- Sand/dust samples are already disintegrated, although there may be slight cementing due to subliming/evaporating frost (?). Any delicate cement would probably not survive transport back.

1.4. Contamination that affects this investigation: Types and limits

Each sample would need to be placed in a separate, hermetically-sealed container. Organic compounds should not be used in the instruments used for sample collection nor in the containers and seals.

1.5. Sample number and mass

Minimum surface and subsurface sample of the regolith. Should also take a sample of rocks of different composition (if present within reach of the landing site or rover capabilities; see above comment regarding sample diversity).

I.e. minimum sample number of 4 of each > 1 g.

1.6. Vulnerability of samples to degradation effects (T, volatile loss, etc.)

The biggest problem would probably be disintegration of a friable sample with possible subsequent loss of volatiles, if relatively volatile components are present to begin with. This is why the sample containers would need to be hermetically sealed so that, if volatiles are liberated during transport (time), they would at least be collected within the container. Exposure to temperatures above 40 °C, would contribute to volatile loss. As Steve Benner noted in his contribution, if you have extracted volatiles in the sample container, there is a possibility that they could further degrade any organics left in the sample.

1.7. max sample temp to achieve objective

≤ 40°C

1.8. Impact of degradation effect on the investigation

See comments in 1.6.

1.9. Required/preferred sampling hardware

Scoop and drill/mole without organic components

1.10. Data needed for sample characterization, sample selection decisions

Observational and geochemical/mineralogical data to determine the composition of the sample, its origin, and its status (e.g., loose regolith, friable sediments/weathered volcanics, solid rock).

1.11. Estimate of required mobility range

As much as possible to obtain as wide a variety of samples as possible, i.e., at least 2 km

1.12 Special requirements for sample acquisition, storage, and Earth analysis?

- Characterisation of the sample site/materials before acquisition
- Storage in separate, hermetically-sealed containers
- No organic components in sample acquisition tools or storage containers

- Care in opening the containers on Earth so that any eventual volatiles liberated during transport could be analysed.

C. Objective: Assess whether life is or was present on Mars

C1. Investigation: Characterize complex organics.

Team leads: Eigenbrode, Benner, Conrad, Glavin, Steele

The identification of complex organics that can only be produced biologically is a very strong biosignature, if forward contamination by terrestrial organics can be excluded. Measurements for this investigation must include appropriate methods to identify and exclude forward contamination as a source of the target materials. To this end new instruments must be developed for cleaning and monitoring of spacecraft contamination. Instruments must be required to produce procedural blanks that allow accurate measurements by that instrument to be undertaken. This would entail that the critical path of contamination, i.e., the path the sample takes to the instrument, be cleaned to a level below the detection limit of the instrument. Example measurements might include characterization of organics such as DNA, nucleotides, chlorophyll, etc. for extant life; hopanes, steranes, isoprenoids, etc., for fossil life; or cumulative properties and/or distributions of organics such as homochirality.

One of the first assessments of biological processes would consist of characterization of complex organics. The distribution of organics on Mars is currently unknown beyond the observation that they are not abundant at sites investigated to date. Thus, this investigation currently entirely overlaps Goal 1, B1 Determine the distribution and composition of organic carbon on Mars. Please see sample requirements listed under Goal 1, B1 for this investigation.

Additional comments. Complex organics could be present in various forms including biomolecules, cross-linked humic-like macromolecules, and kerogen. Within each subgroup, the structural and heteroatomic nature could vary. Although the sampling requirements for addressing this investigation and the vulnerability to alteration and contamination are the same as those described in section B1, most analyses of complex organics would require specific sample preparation targeting types of organic material. For instance, wet-chemical extraction or hydrolysis by water or acid might be necessary prior to analysis of amino acids, amines, carboxylic acids, etc. that are bound in large molecular structure or within the mineral matrix. Various unbound components are accessible by solvent extraction, as is necessary for hydrocarbons such as polyaromatic hydrocarbons, alkanes, and possibly lipids. In both cases, derivatization of active functional groups might be desired to focus the analysis on specific compound groups, such as in the chiral analysis of amino acids. More general organic characterization by pyrolysis-MS and GCMS, Raman, etc. might serve as a guide for determining appropriate sample quantities and preparation techniques.

Molecular information yields increase when structural integrity is maintained during processing for both unbound and bound complex organics. Thus analytical techniques that involve minimal processing would be preferred. The analytical suite would need to structurally identify and resolve a breadth of compounds, their isotopic composition, and heteroatomic content in order to identify molecular biosignatures, exogenous and indigenous abiogenic organics. As with all investigations of organic carbon on Mars, the geological and geochemical context of samples must be well documented during sample selection and upon return in order to

assess sources and processes influencing organics, especially biological sources. Moreover, the distribution and isotopic composition of inorganic carbon and simple organic volatiles are necessary to build the framework for understanding the biogeochemical cycling of carbon on Mars.

C2. Investigation: Characterize the spatial distribution of chemical and/or isotopic signatures.

Team leads: Des Marais, Eigenbrode, Pratt, Sumner

The spatial distribution of chemical or isotopic variations can be a biosignature, if the distribution is inconsistent with abiotic processes. Example measurements might include imaging of the distribution of organics on a surface or in minerals; identifying correlations among isotopic values and elemental concentrations that reflect biological processes; or the presence of reduced and oxidized gas phases in disequilibrium.

A biosignature is an object, substance and/or pattern whose origin specifically requires a biological agent. The usefulness of a biosignature is determined by both the probability of life creating it and the improbability of nonbiological processes producing it. Living systems can create biosignatures as remnant expressions of their complexity, for example, complex organic molecules or organismic structures such as cells, leaves or skeletons. Living systems also create biosignatures as byproducts of their energy harvesting processes. Examples include the accumulation of sedimentary organic carbon or stable isotopic patterns in sulfate and sulfide minerals or reduced carbon and carbonates. This investigation would address samples that might contain traces of chemical or isotopic biosignatures.

Sample types needed. Samples from materials that experienced formerly habitable environments would be prime candidates for this investigation. In particular these are substances that contain the elemental building blocks of life, in particular C, N, H, S, P and certain transition elements such as Fe and Mn.

Sample diversity needed. Aqueous sediments in layered sequences should be taken from appropriately spaced stratigraphic horizons that allow their depositional environments to be characterized. Igneous bedrock and float might harbor evidence of C, N, S and P minerals in cracks, voids or alteration zones. Should a hydrothermal deposit be discovered, sequences of samples along paleo-temperature, paleo-flow lines and/or paleo-redox hydrothermal gradients would help to define their environments of formation, including potential biogenic signatures in textures or elemental and isotopic distributions.

Physical condition (rock, pulverized rock, etc.). Rock chips and cores would be optimal because they would best preserve minerals containing C, N, S and P and the information contained in their spatial distribution. Pulverized rock might be useful for chemical analyses of any of these phases, but would not preserve the micron-scale spatial gradients targeted in this investigation.

Contamination types and limits that affect this investigation. Samples should not be exposed to conditions that might alter the chemical and isotopic composition of any trace C, N, S and P phases. Returned samples should be hermetically sealed.

Sample number and mass. The requirements for mineralogical context, the expected (relatively minor) abundances of these minerals and contamination concerns would call for individual sample sizes in the range 1 to 5 grams, especially for textural analyses. Chemical and isotopic analyses likely could be performed with samples <1 gram. The composition of host phases, together with the anticipated need to sample stratigraphic sequences (minimum 3-5 samples), soil profiles (minimum 3-5 samples) or geochemical gradients (minimum 3-5 samples) indicate that at least ten carefully selected samples would be required for this investigation.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Temperatures that exceed maximum Mars ambient temperatures at the site of collection might alter any bicarbonates and polyhydrated sulfates present. Large changes in relative humidity can alter nitrates and polyhydrated sulfates.

Maximum sample temperatures for sample integrity. Keeping samples below maximum Mars ambient conditions would achieve 100% of the objective. Sample handling and storage temperatures that exceed 50°C would alter hydrated minerals and could affect oxygen isotopic patterns. Finely disseminated minerals might begin to exchange isotopically with water vapor above 50°C. Storage containers should be hermetically sealed.

Impact of degradation on the investigation. Elevated temperatures could decompose certain minerals, destroying spatial elemental and isotopic gradients and disrupting microscale diagnostic sedimentary textures. Sealed containers would be a priority in order to preserve all components and maximize the possibility of “reconstructing” any materials altered during sampling and transport to Earth.

Required/preferred sampling hardware. Rock corers that achieve minimal heating during sampling. Sample handling that would heat the samples only minimally.

Data needed for sample choice and in situ characterization. Image the rock outcrop or regolith sampling site to document their macroscale textures and any indications of their composition and origin. Perform spectroscopic (NIR or MIR) and elemental abundance measurements to guide selection of optimal samples.

Estimate of required mobility range. The need to land at a safe (flat) site would require mobility of several km in order to approach and sample key localities such as stratigraphic sequences, hydrothermal deposits, etc. and to perform observations to acquire geological and environmental context.

C3. Investigation: Characterize the morphology or morphological distribution of mineralogical signatures.

Team leads: *Westall, Sumner*

Sedimentary and weathered rocks can preserve biosignatures in the distribution of grains and minerals or in the morphology of biologically produced minerals. Example measurements might include micron to nanometer imaging and chemical analysis of crystals or morphological characterization of sedimentary lamination to regional or global scale characterization of sedimentary stratigraphy.

Geological setting – Samples from rocks that have been influenced by water would be required – either formed by deposition/precipitation/extrusion in water, or water flowing through cracks in

the rocks (runoff water, standing water, hydrothermal fluids). Weathered surfaces (altered by water) can also contain morphological biosignatures.

Characterisation of the morphology and distribution of mineralogical biosignatures would require intact samples because morphological signatures depend on spatial distributions of features. Potential mineralogical biosignatures must be evaluated within the context of the rocks. Loose sand and powders do not conserve the context although they may contain biologically-produced minerals. On a larger scale than returned samples, biolaminations may be of the order of tens of microns to centimeters. These should be imaged prior to sample collection.

Sample types needed. Highest priority samples would be intact sedimentary rocks that formed in bodies of standing water because they can support biofilms with significant morphological expression and aggrading environments readily preserve biofilm morphology. Chemical sediments formed in evaporitic and hydrothermal environments would be high priority due to the prevalence of mineral precipitation that promotes preservation of morphological signatures. Water induced mineral precipitation within cracks in rocks, including volcanic rocks can also capture morphological biosignatures. Duricrusts, desert varnish, and weathered horizons can also preserve small-scale morphological biosignatures. Volcanic rocks extruded under water can encapsulate or be colonized by micro-organisms that leave morphological biomarkers.

Sample diversity needed. Diversity including the rock types above would be desired. A suite of samples representing these rock types at the landing site would be needed.

Physical condition (rock, pulverized rock, etc.). Intact rock samples would be necessary, including lithified rock as well as friable sediments or weathered volcanics.

Contamination types and limits that affect this investigation. There would be less of a problem of cross-contamination with mineral biosignatures than there would be with chemical ones but it is important to be able to relate each individual sample to its microhabitat and the *in situ* documentation of that habitat in order to make reliable interpretations of the potential mineral biosignatures within samples. Thus, the samples would need to be isolated from each other to prevent cross contamination during transport. Sampling with a clean tool would be desirable.

Sample number and mass. A suite of 5 samples of 5 grams each would be desired. Sample size would be determined by the need to resolve spatial variations on the centimeter and finer scale more so than mass. Samples would need a dimension of 1 cm or more in at least one direction to allow adequate spatial evaluation.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). The main degradation hazard would be the loss of integrity of delicate (friable) rocks, especially if they are stratified or if the mineralogical biosignature of interest becomes loosened from its mineralogical matrix. Textures would be degraded if temperatures are sufficiently high to induce phase changes in hydrous minerals or a substantial concentration of volatiles are lost.

Maximum sample temperatures for sample integrity. Temperature degradation can destroy mineralogical biosignatures preserved in hydrated phases. Temperatures equivalent to ambient martian environments for the sample would be strongly desired and would be required for hydrous samples. Anhydrous samples could probably withstand temperatures of 20°C during sample return with a short exposure to 50°C on landing without compromising the highest priority scientific investigations.

Impact of degradation on the investigation. Loss of integrity of delicate samples would significantly limit the quality of results for this investigation. The degradation of hydrous samples would also destroy textural information, possibly destroying biosignatures.

Required/preferred sampling hardware. Clean coring or a mechanical finger to pick up rock fragments that are clearly related to the underlying rock context.

Data needed for sample choice and in situ characterization. The sample would need to be imaged prior to collection to document in situ structures (sediment lamination, biolaminations) and the relationships between potential biominerals/mineralogical biosignatures and the host rock and surrounding environment. The host rock mineralogy and geochemistry would need to be characterized to determine the composition of the sample and to provide environmental context. Characterization of host rock would be especially important for small samples.

Estimate of required mobility range. As much as possible to obtain as wide a variety of samples as possible, i.e., at least 2 km

C4. Investigation: Identify temporal chemical variations requiring life.

Team leads: Steele, Benner, Neilson

Extant life may be active, producing observable temporal changes in chemistry over the time scale in which a lander experiment may be functional. Monitoring systems that may harbor life is an excellent way to identify the presence of life. However, possible abiotic reactions need to be thoroughly understood and forward contamination needs to be identified or excluded. It is critical that measurements capable of being contaminated include appropriate methods to identify and exclude forward contamination as a source of the signatures being monitored. Example measurements might include monitoring the flux of gases thought to be biologically-produced; monitoring oxidative changes in a way that excludes abiotic reactions; or performing experiments to look for metabolic processes.

The identification of temporal chemical variations requiring life would be the most important analytical tasks for returned samples due to planetary protection considerations in addition to looking for evidence of life on Mars. The critically important planetary protection evaluation of returned samples would drive sampling requirements beyond those articulated here, which focus on the scientific aspects of identifying temporal chemical variations requiring life. However, the following requirements could form the basis for defining sample requirements for planetary protection.

The Viking experiment to monitor the kinetics of reaction and gaseous release of the Martian regolith with a medium over time is one of the mainstays of terrestrial microbiology. Monitoring changes in morphology of interesting features has also revealed the nature of contaminants in Martian meteorites on Earth. Extant and viable life will affect its surroundings, changing the concentration of key nutrients and waste products. There is no reason to assume that an extant Martian organism would do anything less. There are however, fundamental difficulties associated with undertaking these observations as illustrated with the Viking experiments. Namely: ensuring no abiotic reactions cause a false positive (although these reactions would be of interest in themselves), ensuring that no terrestrial contamination is involved, ensuring the integrity of the sample during acquisition, storage, transport, curation and experimentation on earth. Temporal changes might be monitored in a variety of ways, imaging of the same sample

over a period of time (Toporski and Steele 2007), radioisotope uptake and release, gaseous exchange, culturing etc. Throughout this process, it would be essential to conduct analysis at appropriate time steps to garner the most information while ensuring that during measurement the analysis would not be compromised i.e., all the gas would not be removed from the headspace in the first time step.

Sample types needed. Ideally subsurface samples would be best to answer this goal. However, it is likely that, if present, Martian biota would adapt similar survival techniques to earth biota and retire within rocks and become endolithic in character. Obviously samples that contain evidence of organic carbon, hydrated minerals and the presence of known redox couples that could be exploited by life would have a high priority. Any returned samples with liquid or solid phases should be subject to analysis for temporal changes requiring life.

Sample diversity needed. Given the unknown nature of possible Martian organisms and the absence of positive detections of organics on Mars to date, sample diversity can not yet be defined. However, all returned samples should receive attention particularly those containing organic carbon

Physical condition (rock, pulverized rock, etc.). This goal represents a diverse range of investigations, some of which could and should be undertaken on fresh fracture surfaces, some on pulverized material that would be handled in such a way as to ensure NO organic or microbial contamination to the samples.

Contamination types and limits that affect this investigation. A single terrestrial microbe would potentially compromise these investigations, given that terrestrial microbiota can thrive on organic material within Martian meteorites. Organic contamination may be tolerated up to a concentration below the detection limits of the instrumentation used to measure it, particularly if conditions did not favor reactions that would produce temporal changes.

Sample number and mass. As previously alluded to, most samples would have to be processed. All investigations on this material could be carried out on ~6 g of pulverized material (assuming 3 samples at 2 grams per sample), plus a variety of fresh fracture surfaces (~3 samples of 1g per samples from diverse areas of the whole sample).

Vulnerability of samples to degradation effects (T, volatile loss, etc.). We have no way of knowing what a Martian organism may be vulnerable to. However, it would seem prudent to subject the samples to Martian ambient conditions during sample return.

Maximum sample temperatures for sample integrity. Ambient Martian conditions would be required to avoid disruption of any microbial ecosystems present.

Impact of degradation on the investigation. Degradation would result in a null result.

Required/preferred sampling hardware. Sterilized instruments would be required for sampling.

Data needed for sample choice and in situ characterization. Detection of any biosignature from images or the detection of organics prior to sampling would increase the reliability of results by providing context for the sample.

Estimate of required mobility range. Sufficient mobility to obtain sample diversity would be desired.

Additional comments. Sterilization of instruments and other hardware that would contact or could contaminate the sample would be strictly required.

GOAL II

Introduction and Synthesis

This Goal focuses on understanding the climate evolution and history of Mars through atmospheric processes, surface-atmosphere interaction, climate history expressed in polar layers, and understanding atmospheric conditions critical to safe landing of spacecraft. Many of the specific objectives and investigations related to dynamical processes of the atmosphere which need to be measured in-situ and so are largely irrelevant to sample return. Sample return was found to support only specific investigations under Objective B: Mars Ancient Climate and Climate processes. Investigations B.1 and B.3 are related and linked to the determination of noble gasses and trace atmospheric constituents, both of which would benefit from a return atmospheric sample and analysis of gas inclusions in return rocks. Investigation B.4, records of past climates, has strong synergy and overlap with many of the Goal III objectives and sample return requirements for Goal 3 would satisfy the needs for this investigation as well. Investigation B.5 of polar ice and layered deposit stratigraphy would benefit from the return of a sample of ice, or small core. Return of specialized atmospheric and/or ice samples is expected to profoundly impact our understanding of climate evolution and history as outlined in the Goal.

II. GOAL: UNDERSTANDING THE PROCESSES AND HISTORY OF CLIMATE ON MARS

The fundamental scientific questions that underlie this goal are how the climate of Mars has evolved over time to reach its current state, and what processes have operated to produce this evolution. These extremely important scientific questions are in accord with several key science objectives found in the NASA Solar System Exploration Roadmap (2003). Mars climate can be defined as the mean state and variability of its atmosphere and exchangeable volatile reservoirs (near the surface) evaluated from diurnal to geologic time scales. An understanding of Mars climatic evolution rests upon gaining a full understanding of the fundamental processes governing its climate system, and thus upon obtaining detailed observations of the current (observable) system. Goal II also is in line with the recent recommendation of the Solar System Exploration Survey [2002], which calls out the clear need for Mars upper atmosphere measurements to properly characterize current volatile escape rates. The Objectives below are given in priority order. Objective A is crucial to understanding the present state of the entire atmospheric system (from the surface-atmosphere boundary to the exosphere). It forms the baseline for interpreting past climate on Mars. Objective B focuses upon specific investigations that would measure key indicators of the past climate of Mars. Finally, Objective C highlights mission critical atmospheric measurements that would reduce mission risk and enhance overall science return, benefiting all future missions to the planet. No attempt has been made to prioritize these risk mitigation and engineering related measurements since all are important.

A. Objective: Characterize Mars' Atmosphere, Present Climate, and Climate Processes (investigations in priority order)

Our understanding of the composition and dynamics of the present Martian atmosphere is the basis for understanding past climate on Mars. Investigations of both the upper and lower atmosphere are essential because they are one large, interconnected system. Measurements of both atmospheric regions would enable us to explore different suites of processes that play unique roles in understanding the Martian climate and its evolution. In short, a ground-to-

exosphere approach to monitoring the Martian atmospheric structure and dynamics is needed for a proper characterization of the present day climate of Mars.

1. **Investigation: Determine the processes controlling the present distributions of water, carbon dioxide, and dust by determining the short and long-term trends (daily, seasonal and solar cycle) in the present climate. Determine the present state of the upper atmosphere (neutral/plasma) structure and dynamics; quantify the processes that link the Mars lower and upper atmospheres.**

Implications for sample return.

Discussion Leads: **Steve Bougher**

The processes and detailed atmospheric characterizations outlined in this broad investigation would be best addressed with a combination of global orbiter, network, and landed/rover measurements conducted over multi-year (continuous) timeframes. A single returned atmospheric sample would not contribute to the completion of this investigation.

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2. **Investigation: Search for microclimates.**

Detection of exceptionally or recently wet or warm locales, exceptionally cold localities, and areas of significant change in surface accumulations of volatiles or dust would identify sites for *in situ* exploration. This requires a global search for sites based on local surface properties (e.g., geomorphic evidence, topography, local thermal properties, albedo) or changes in volatile (especially H₂O) distributions.

Implications for sample return.

Discussion Leads: **Vicky Hipkin**

This objective, as it stands, focuses on detecting environments and not on characterizing these. In this case sample return would not be relevant.

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3. **Investigation: Determine the production/loss, reaction rates, and global 3-dimensional distributions of key photochemical species (O₃, H₂O₂, CO, OH, CH₄, SO₂, etc.), and their interaction with surface materials.**

Implications for sample return.

Discussion Leads: **Joel Levine** and Don Bogard

Because a returned atmospheric sample would be in a different environment, photochemical species would undergo substantial equilibrium changes relative to that in Mars' atmosphere. Interpretation of atmospheric composition and chemistry would be very difficult, if not impossible. Gas inclusions in returned rock samples would be unlikely to provide useful information on photochemical state of the martian atmosphere. Therefore sample return is not seen as relevant to this investigation.

B. Objective: Characterize Mars' Ancient Climate and Climate Processes

Through Study of the Geologic and Volatile Record of Climate Change (investigations in priority order)

Understanding the ancient climate and climate processes on Mars requires interdisciplinary study of the Martian surface and atmosphere. The investigations described below would focus on quantitative measurements (concentrations and isotopic compositions) of important atmospheric gases in the atmosphere and trapped in surface materials. It also would require study of geologic features to search for the record of past climates.

1. Investigation: Determine the stable isotopic, noble gas, and trace gas composition of the present-day bulk atmosphere.

These provide quantitative constraints on the evolution of atmospheric composition and on the sources and sinks of the major gas inventories. It is important to understand the temporal and spatial variability of atmospheric composition. This investigation would require high-precision isotopic measurements of the atmosphere.

Implications for sample return.

Discussion Leads: **Don Bogard.** James Farquahar, Veronika Heber, Kurt Marti

Current and Anticipated Knowledge.

Measurements from Earth and on Mars by Viking demonstrated significant isotopic fractionations of H and N in the martian atmosphere, which indicate substantial atmospheric loss of these species over time. Measurements of martian meteorites have demonstrated analogous isotopic fractionations in atmospheric Ar and Xe, but curiously not Kr. Atmospheric composition of Ne is very poorly known. Although these data suggest the martian atmosphere possibly experienced both an early massive loss and a continuing loss by different mechanisms, details of its evolution are poorly known. Further, direct measurements from orbit of H loss from the upper atmosphere suggest that the present atmospheric D/H ratio could have been produced in a far shorter time than the age of Mars, which implies periodic internal degassing of water may replenish atmospheric H. More detailed understanding of such atmospheric loss mechanisms have implications for understanding evolution of the Earth's atmosphere. Because atmospheric fractionation during planetary escape must be interpreted in terms of initial composition and condensed buffers (e.g., hydrates and carbonates), this investigation is closely linked with investigation B-3, which would address ancient atmospheric volatiles trapped in martian samples.

Carbon dioxide is the principal carrier for both carbon and oxygen in the martian atmosphere, and a high precision determination of its isotopic composition has the potential to provide very important constraints on the steady state carbon and oxygen cycles (source and sink flux terms) of present-day Mars. Further determination of the isotopic fractionation of carbon and oxygen isotopes between carbon dioxide and other atmospheric species has the potential to provide additional information that would be important in placing constraints on these element cycles. Viking measurements of atmospheric C and O were only accurate to $\pm 5\%$, whereas C measurements in meteorites demonstrate the expected isotopic fractionations on a smaller scale that are produced during solid/liquid/gas phase chemical reactions. The H isotopic compositions measured in meteorites are much lighter than that of the atmosphere, exhibit variations, and the initial (interior) D/H ratio is still controversial. All volatile data acquired from meteorites represent components incorporated at earlier times, and may or may not be the same as the

atmospheric composition today. For trace, chemically-reactive species in the atmosphere, only the Viking compositional data exist.

Required Measurements. The isotopic abundances of all abundant and/or chemically unreactive species in the martian atmosphere (e.g., CO₂, N₂, Xe, Kr, Ar, Ne) should be accurately measured. Where feasible abundances of minor species (H, He, CO, sulfur compounds) should also be measured. Measurement of ¹⁴C activity might also be desirable. These measurements would be performed by mass spectrometry and other appropriate techniques in multiple terrestrial laboratories. Gas handling procedures and measurement techniques differ among the gases, and returned volatiles would have to be subdivided.

Most noble gases and abundant volatile species could be measured on a gas sample size of 0.1 to 100 pico moles. Some species could be measured on the same sample, e.g., noble gases, whereas others would require separate gas splits. The table below gives an approximate amount of gas in pico moles needed for a single analysis and the volume of Mars atmosphere at ambient conditions that would be needed to supply this analysis amount. This assumes Mars atmosphere is 0.007 that of Earth's at STP.

GAS	Assumed for Analysis	Mars Atmosphere Required in cubic cm, ambient
Xe	0.1 p-mole, e-9 cc	2
Kr	0.1 p-m, e-9 cc	0.5
Ar	1 p-m, e-8 cc	0.0001
Ne	1 p-m, e-8 cc	1
CO ₂	100 p-m, e-6 cc	0.1
N ₂	10 p-m, e-7 cc	0.02
H/D	5 nano-mole (e-4 cc)	~50

From this ~ 100 cubic cm of Mars atmosphere at ambient conditions would be sufficient for multiple analyses of noble gases and abundant species. Note, however, these numbers for H/D in water are approximate only. Note also that the head space inside a container of solid samples, if hermetically sealed, could possibly satisfy the above sample sizes.

Samples Needed. Determination of the current martian atmospheric composition would require return of an atmospheric sample. Atmospheric noble gases, CO₂, and N₂ could possibly be returned in the same container as solid material, but advantages and disadvantages of a separate atmosphere container, especially for other minor components, should be evaluated. The atmospheric gas container should be constructed in such a way that the gases can be readily removed without contamination in a terrestrial lab. Several isotopic abundances could be measured in an atmospheric sample of 100 cm³ collected at Mars ambient (~0.7 cm³ STP). However, measurement of several rarer isotopic abundances and multiple analyses in different labs would probably require a much larger sample. The possibility of compressing an atmospheric gas sample above Mars ambient pressure should be investigated.

Special Requirements. Sufficient hermetic sealing to prevent gas loss during return would be important, and the reliability of the actual seal might be an issue. Whereas measurements of noble gases, CO₂, and N₂ should be straightforward in a returned atmospheric sample, the less abundant, chemically reactive species (e.g., O₂, H₂O, CO, sulfur compounds) likely would be altered during return. Special consideration should be given to volatile outgassing of the

atmospheric container, especially during hermetic sealing operations. Consideration should also be given to chemical reactions of the gas sample with the returned container. Measurement of these trace species might better be performed on Mars.

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- 2. Investigation: Determine the rates of escape of key species from the Martian atmosphere, their correlation with seasonal and solar variability, their modification by remnant crustal magnetic fields, and their connection with lower atmosphere phenomenon (e.g. dust storms). From these observations, quantify the relative importance of processes that control the solar wind interaction with the Mars upper atmosphere in order to establish the magnitude of associated volatile escape rates.**

Implications for sample return.

Discussion Leads: **Steve Bougher and Bruce Jakosky**

Isotopic ratios analyzed from an extracted atmospheric sample would serve as a "tie point" and general aid in our understanding of volatile escape rates determined for the II.B.2 investigation. However, a direct link between an atmospheric sample and quantification of volatile escape rates is missing. Thus, analysis of an atmospheric sample would complement Investigation II.B.2. However, such a returned and analyzed atmospheric sample would be most directly relevant to investigations II.B.1 and II.B.3.

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- 3. Investigation: Determine how the stable isotopic, noble gas, and trace gas composition of the Martian atmosphere has evolved through time.**

These provide quantitative constraints on the evolution of atmospheric composition and on the source and sinks of water and other major gas inventories. Requires high precision dating and isotopic measurements of Martian meteorites and returned samples, and high precision *in situ* measurements of samples on and beneath the surface (e.g., polar layered-deposits or strata exposed in Valles Marineris).

Implications for sample return.

Discussion Leads: **Don Bogard**, James Farquhar, Bob Pepin, Veronika Heber, Kurt Marti, and Monica Grady

Current and Anticipated Knowledge.

The most current, sketchy knowledge about evolution of atmospheric composition through time derives from analyses of martian meteorites, which contain volatiles of varying and often unknown age. These meteoritic volatiles occur in various phases, including adsorbed on solid surfaces, shock-implanted into solid silicates (including impact melt), and as chemically condensed phases such hydrates and carbonates, likely precipitated by ground water interactions with silicates or by chemical reactions induced by impact heating. Other martian surface samples might contain subsurface ices. An important approach to gaining new information would be to analyze various volatiles in different types of samples of determined age.

An important element in understanding atmospheric evolution is knowing the primitive, starting composition of atmospheric volatiles and the physical method by which they were introduced into the atmosphere, i.e., by interior degassing or late-stage accretion (e.g., from comets). The

isotopic composition of most atmophile elements are either too poorly known or are too fractionated to currently address this question directly, but the atmospheric Kr isotopic composition resembles the solar composition. Further, heavy noble gases in a few meteorites (e.g., Chassigny) also indicate a solar-like starting composition. The crustal $^{15}\text{N}/^{14}\text{N}$ ratio measured in some meteorites is very different from the atmospheric ratio and similar to, though not exactly like, the terrestrial composition. Samples from the Earth's interior show solar-like Ne and possibly Ar. It also would be important to determine the primitive (starting) D/H composition in order to assess possible short-term variations over time produced by interior degassing and rapid atmospheric loss. Models that have been suggested for atmospheric loss processes strongly utilize measured isotopic compositions of atmospheric species.

The martian interior likely is poorly degassed of its volatiles. Measurement of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio (where ^{40}Ar derives from the decay of ^{40}K over geologic time) in ancient atmospheric gas trapped within samples of known age could directly address the martian degassing history. Further, measurement of the $^{129}\text{Xe}/^{132}\text{Xe}$ and $^{136}\text{Xe}/^{132}\text{Xe}$ ratios (where ^{129}Xe and ^{136}Xe derive from decay of ^{129}I and U, Pu, respectively) in igneous samples that formed in the crust or mantle can and has yielded inferences about very early planetary processes. For example, the $^{40}\text{Ar}/^{36}\text{Ar}$ and $^{129}\text{Xe}/^{132}\text{Xe}$ ratios in the martian atmosphere are larger than apparent trapped noble gases in igneous martian meteorites, just the opposite from the observation on Earth, and this probably conveys information about mobility of the parent elements during early planetary differentiation.

Comparison of isotopic compositions of elements like C, O, H, and S in various chemical forms and in different phases of returned samples could give a potential wealth of geochemical information about atmospheric and volatile interactions and evolution. These light elements isotopically fractionate, in generally predictable ways, between any two phases (gas/liquid/solid) in chemical equilibrium. Thus, precise isotopic measurements of these elements in returned samples could give information on the kind of chemical process and possibly the temperature that produced the analyzed phase. These data could provide information about genetic relationships among sulfur and oxygen-bearing phases, the oxidation pathways for compounds in the regolith that involve atmospheric species with anomalous oxygen isotope compositions (speaks to oxygen sinks), and the sources and mixing of martian sulfate. Further, comparison of isotopic compositions of an element in two phases having similar origins but different ages might give information on changes in isotopic composition of the atmospheric inventory over time. Because CO_2 in the martian atmosphere is likely an important part of carbonate formation in surface rocks, it would be important to accurately measure its isotopic composition (see B-1). It also is highly desirable to measure the C, O, and H compositions in condensed polar deposits, as they act as chemical buffers on the atmospheric composition. A related question is where most of the surface inventory of CO_2 (estimated at possibly ~20 meters of carbonate) is currently located. Another possibility is determining to what extent non-linear isotopic fractionation effects, produced in some atmospheric elements on Earth (and detected in martian meteorites), could be measured in returned samples and used as a further determinant of gas/solid phase reactions.

In many of the above studies accurate age dating of some portion of the returned samples would be desired (see Goal III). Although igneous samples are more easily dated, age dating of chemically precipitated phases has been performed on terrestrial samples and on one ancient martian meteorite.

Required Measurements. Measurement of the isotopic composition of the trapped noble gases, C, O, H, N, and S in various phases, including trapped atmospheric gas, chemical precipitates, and igneous and sedimentary rock.

Sample types needed. Ideally, it would be desirable to return a diversity of sample types, including igneous and sedimentary rocks, precipitates from chemical reactions as may occur in veins and voids within samples, and impact melts that may contain ancient atmospheric gases. Because concentrations of cosmogenic Ne, Kr, and Xe in samples having long surface exposure times may approach trapped gas concentrations, samples with shorter exposure times would be preferable for these measurements. The sample size required for a measurement would depend on the particular analysis and might vary from less than a milligram to 100 mg. Most analyses would probably require samples some 10s of mg in size.

It might be desirable to analyze gases collected in the sample container or released into the container during return. If so, this container would have to be hermetically sealed (see B-1). Temperature excursions to <100°C for no more than a few minutes might release some lightly-bound volatile species (e.g., water) but should not seriously effect most volatiles. Higher temperatures or longer times should be avoided.

4. Investigation: Find physical and chemical records of past climates.

This investigation centers on finding geomorphic and chemical evidence of past climates or of prior environmental events or conditions that may have perturbed the local or global climate in unexpected ways (e.g., the former presence of an ocean or seas, large impacts, episodic volcanism or outflow channel activity). These provide the basis for understanding the extent, duration (e.g., gradual change or abrupt transition), and timing of past climates on Mars. This investigation would require determining sedimentary stratigraphy and the distribution of aqueous weathering products.

Implications for sample return.

Discussion Leads: Joel Hurowitz, Nicholas Tosca (Harvard University), Sidney Hemming (Columbia University).

According to Cronin in *Principles of Paleoclimatology*, "...three overriding principles govern most paleoclimatological studies. These are the *climate system* itself and the dynamic interrelationships among its component parts; *chronology*, the dimension of time that is the prerequisite to trace changes in climate; and *climate proxies*, the surrogates of climate related parameters..." The first principle is addressed in large part through study of the current Martian climate system, coupled to modeling studies that are capable of making predictions about how the Martian climate system has evolved over geologic time. This is the purview of Investigations in Goal IIA, as well as IIB, Investigations 1-3 and 5. A note relevant to the issue of understanding the climate system through time, however, is that terrestrial paleoclimatologists use ice cores samples in order to perform analyses of the stable isotope composition of the ice (as a temperature proxy) and measure the composition of atmospheric gases trapped in the ice. These ice core records are an invaluable tool for directly sampling ancient atmospheric chemical compositions, and core sampling of the Martian polar ice caps should be given some consideration in the study of ancient Martian atmospheric compositions.

Further analysis of Investigation IIB-4 will concern itself with the issues of chronology and climate proxies, and how one would sample the Martian rock record in order to effectively capture variations in Mars' climate.

Terrestrial paleoclimatologists often turn to layered sedimentary rocks deposited in quiescent subaqueous environments in order to address the issue of *chronology*. Because sediments deposited in such environments are typically layered on relatively short geologic time scales (annual to centennial), it is possible to obtain a high-resolution accounting of climate variation occurring during deposition. Given a bedding layer that could be dated using geochronological techniques (e.g., U-Th-Pb, K-Ar), and some knowledge of the deposition rate of individual layered beds, it is possible to approximate the length of time represented by a given set of samples. Ideally, the "marker bed" used for geochronological analysis would represent a snapshot in time (e.g., a volcanic ash layer, or a chemical precipitate formed directly from an aqueous phase). The isotopic compositions of such materials are typically closed at the time of crystallization/deposition, and assuming they remain closed to subsequent isotopic resetting (e.g., by diagenesis), they form the chronometer against which underlying and overlying layered samples could be compared.

In order to accurately reconstruct the chronology of a sampled section for Mars sample return, one would need to identify cyclically deposited sedimentary materials which are interbedded with layers of volcanic rock and/or chemical sediments precipitated directly from solution. The most practical way to go about identifying the section of interest would be to first: identify the climate variability issue(s) that are of the highest priority to address, and at what time (approximately) in Martian geologic time they occurred. Second, using orbital remote sensing, attempt to identify layered sedimentary rock deposits that appear to have been deposited in a quiescent subaqueous environment. This layered rock deposit should be bounded by geomorphic surfaces having crater retention ages appropriate to an analysis of the climate variation event(s) of interest.

The second issue relates to what *climate proxies* should be used in order to reconstruct aspects of the climate system as recorded by the rocks under investigation. On Earth, a great many climate proxies are based on analysis of biogenic materials and the chemical and isotopic composition of carbonate rocks (yielding information about the fluid phase from which it was precipitated). Unfortunately, for Mars we cannot assume that biogenic materials and/or carbonate rocks will be available, and we must therefore turn to other potential proxies. One such potentially useful climate proxy is the secondary mineral phases present in a given stratigraphic sequence. Changes in the chemistry or mineralogy of environmentally informative minerals across stratigraphy could provide a useful record of a transition in climatic conditions. For example, a transition from a sedimentary sequence dominated by clay minerals and/or carbonates to one dominated by evaporative phases such as halides or sulfates would provide constraints on how fluid chemistry at the Martian surface has varied with time. Such locations in the geologic record could first be identified with orbital spectrometers (i.e., sedimentary contacts between sulfates/halides, or sulfates/clays, carbonates/sulfates, etc.). A full analysis of the mineralogical, chemical and textural characteristics of such materials would yield the requisite information. Geochronologic analysis of key marker beds, and or direct dating of sedimentary minerals would provide constraints on the timing and duration of such an event. Finally, stable isotopic analysis of chemical precipitates might yield further information regarding issues such as fluid temperature, analogous to studies performed on terrestrial samples.

This discussion of climate proxies brings up another potential sampling strategy that differs from the high-resolution sedimentary stratigraphic approach outlined above:

Obviously changes in climatic variables such as temperature, humidity, atmospheric pressure, etc., will be reflected in the physical state of rocks and soils at the Martian surface as they interact with the Martian atmosphere-hydrosphere system. Therefore, in a broad sense, climatologic conditions can be captured through an understanding of the conditions of rock weathering. The rate and extent of rock (or soil) weathering are a reflection of the predominant climate conditions during the time weathering takes place. Thus, a cold and dry climate is likely to result in conditions in which physical weathering predominates over chemical weathering, and vice versa for wetter conditions. The study of weathering profiles (be they weathering rinds on individual rock samples, or meters thick weathering profiles developed on large scale outcrop) would provide a low-resolution snapshot of the average weathering conditions, and therefore climate conditions, which prevailed during the time interval that the weathering occurred.

Using such an approach, the issue of *chronology* could be addressed via isotopic dating of both the igneous rock protolith and the secondary minerals formed as a result of the weathering process. Further analysis of the types of secondary minerals formed during weathering would provide the *climate proxy* necessary to interpret the conditions prevailing while weathering was taking place. For example, a thin rock weathering rind dominated by an assemblage of secondary minerals such as Fe-sulfates, Fe-oxides, and amorphous silica would suggest a low-pH weathering environment in which large volumes of water were not available. Conversely, a thick soil profile developed on igneous bedrock in which clay minerals, Fe-oxides, and (possibly) carbonates dominate the secondary mineral assemblage would suggest a moderate pH weathering environment in which larger quantities of water were available.

The constraints for a Mars sample return of this type of a weathering-based approach would be to identify sample collection sites from orbit that possess igneous rocks and their weathering products, and which represent a large range in geologic age. In this manner, it might be possible to sample different weathering regimes at distinctive periods in Martian geologic history to see how the weathering environment, and therefore the general climate system, has evolved through time.

Sampling strategy: As far as specific sampling strategies are concerned, the requirements for this investigation are probably very similar to those of MEPAG Goal 3, Investigations 2 & 5, which also seek to address issues relevant to water-rock interactions in the Martian surface environment. The following list of sampling capabilities is modified from the above referenced investigations:

1. Clearly it would be desirable to collect multiple samples of autochthonous (in place) rock. For a stratigraphy sampling mission, one would need to analyze the site from orbit in order to ensure that multiple layers of stratigraphic section could be accessed. In other words, if the section is exposed in a cliff face, one would need to design a sample return spacecraft capable of accessing those layers.
2. For rocks sampled from intact sedimentary sections, drill cores or sample chips should be collected with the size of the samples depending on the scale of bedding. For finely laminated units, it might be more realistic to collect chips or blocks of samples that cut across strike. It would be necessary to accurately document the original orientation of collected samples relative to each other in order to reconstruct the stratigraphy back on

Earth. For more massively bedded units, sample collection might be somewhat easier, requiring a minimum of one drill core or sample chip per layer of interest.

3. Experience from MER suggests that most rocks exposed to the current Martian environment possess weathering rinds that are on the order of a few millimeters thick, and so at a minimum, samples should be collected from a few millimeters beneath the rocks' exposed surface. It would also be desirable to collect that portion of the rock sample exposed to the surface environment so as to analyze the secondary phases present in rock weathering rinds formed in more recent geologic time.
4. For the sampling of weathered igneous rocks (as opposed to a sedimentary stratigraphy sampling mission), sampling would ultimately be dictated by the thickness of the weathering profile of interest. As discussed in above, weathering rinds of a few millimeters thickness are to be expected on all rock samples exposed to the ambient Martian environment. Drill cores placed into igneous rock samples should attempt to collect both the weathering rind and the relatively pristine igneous rock below. For more extensively weathered igneous materials, the approach would be analogous to that of a stratigraphy sampling protocol. The desire would be to collect individual core, chip, or block samples from varying positions in the weathering profile that sample unaltered protolith, moderately weathered material, and extensively weathered igneous rock.
5. Characterization of sampling context would also be desirable. This could vary over scales of ~1 m to several meters depending on the environment, and could include any or all of the following capabilities.
 - a. Context imaging on scales ranging from <20 microns (scale of microtextures) to about 2 m (scale of bedforms). The intent here would be to get as much in situ textural information as possible so that if a sample changes, the original character of the sample could be reconstructed.
 - b. Use of a micro-analytical spectrometer (e.g., Raman microprobe) on samples to be collected could be valuable. In this manner, if the sample did undergo textural changes during transport as a result of changes in temperature or relative humidity, mineralogy could be tied directly to texture (e.g., size, morphology of sediment grains and/or crystals in a specific facies that are associated with a specific chemical or mineralogical signature) prior to sample disturbance.
 - c. If possible, remote mineralogic characterization might make a valuable complement if the resolution of the instrument is similar to the sampling scale of those materials to be returned to Earth. In this manner, understanding of the changes in mineralogy across stratigraphy could be extended above and below the sampled area.
6. Preferred capabilities would be to monitor and, if possible, control relative humidity and temperatures. This might be particularly relevant if the stable isotope composition of hydrated minerals and/or trapped gas phases could be significantly altered by changing temperature and relative humidity during transport to Earth. Laboratory experience shows that sulfate minerals are particularly sensitive to temperature and relative humidity effects.

7. Cross-contamination levels of <1% (and preferably <0.1%) would be required for chemical and isotopic analyses on Earth. Capability would be needed to evaluate potential contamination through imaging of the entire sampling stream (e.g., drill, scoop, inlet).

5. Investigation: Characterize the stratigraphic record of climate change preserved in polar layered deposits, residual ice caps, other climate-modulated deposits of H₂O, CO₂, and dust found elsewhere on the planet.

The presence of extensive layered deposits suggests that the climate of Mars has undergone frequent and geologically recent change. A key to understanding the climatic and geologic record preserved in these deposits is to determine (i) the relative and absolute ages of the layers, (ii) their thickness, extent and continuity, (iii) their petrologic/geochemical characteristics (including both isotopic and chemical composition), and (iv) the environmental conditions and processes that were necessary to produce them. Specific examples of the type of information these deposits may preserve include a stratigraphic record of volatile mass balance; insolation variations; atmospheric composition; dust storm, volcanic and impact activity; cosmic dust; catastrophic floods; solar luminosity (extracted by comparisons with terrestrial ice cores); supernovae and perhaps even a record of microbial life. Addressing this investigation would require high-resolution imaging, *in situ* and remote sensing measurements of stratigraphy and layer properties, and absolute ages determined either *in situ* or from returned samples.

Implications for sample return.

Discussion Leads: **Kathryn E. Fishbaugh**, Michael Hecht, David Fisher, Shane Byrne, and Wendy Calvin, Oded Aharonson

RETRIEVING A POLAR SAMPLE

In this short report, we briefly describe factors to consider if retrieving a sample of polar material in the context of a Mars sample return. We have decided to organize this report by sample type/location since the technology considerations and, in part, the scientific rationale for each are different. However, the overall scientific benefit of retrieving a polar sample would be shared by all sample types: of all possible samples from all parts of Mars, polar samples potentially provide the best insight into the water and climate history. The Polar Layered Deposits represent a detailed record of recent Mars climate history. The composition of material from approximately the top 100 m of ice would reflect the influence of meteorology, depositional episodes (volcanic, impact, dust storms), and planetary orbital/axial modulation over the timescales during which these vary (of order 100 kyr -1 myr). One or more samples from such depths, either in solid or liquid form, would provide critical information on the atmospheric-surface water cycle via hydrogen and oxygen isotopic composition, aeolian material via incorporated impurities, and other particles delivered by volcanic or impact processes. Returned samples would enable absolute age dating via dissolved gas analysis, as well as searching for trace organics (e.g., methane). Samples smaller than a few g would typically be sufficient for the analysis.

General Considerations

For all samples, images of and spectroscopic data from the sampling site would aid in placing the sample in the broader context of the relevant polar region as a whole and in tying it to orbital data. Of low cost but high scientific return for any polar landed mission would be a meteorology package, providing wind direction and speed and atmospheric pressure and humidity; such measurements could be used as ground truth for global climate models and to better constrain the local (volatile) depositional environment. We mention minimum needed core lengths, but longer cores would of course provide more stratigraphic information from further back in time. Cores could be broken into smaller pieces as long as their stratigraphic position is known. Of course, while it is always true that we could reap richer rewards from having several samples from several locations, one sample would provide all of the scientific results described below. As long as the location and geologic unit from which the sample came is known and could be placed in the context of orbital spectroscopic and image data, it would not be necessary to obtain one sample from relatively clean ice and one from relatively dusty ice nor would it be necessary to choose very specific sample sites in order to obtain maximum scientific benefit. Any site within the residual cap or layered deposits would be fine. Isotopic analysis of ice and meltwater for dating purposes would require no larger of a sample than what would be needed from a rock or rock powder sample (a few cm³).

Short Ice Core Sample from the Southern Residual Polar Cap:

The southern residual polar cap is composed of CO₂ ice. Deposition of residual cap layers is highly sensitive to changes in the global environment and is linked to dust storm activity, obliquity, season of perihelion, elevation, and the effect of global topography on atmospheric circulation patterns. It is thought that CO₂ residual caps may form and disappear relatively quickly, so that we may be witnessing a special time in Mars' history, and it is yet unknown whether such a deposit ever formed in the north. With a sample core 20-30 cm in length, one could potentially determine the amount and composition of CO₂ and dust deposited over a full annual cycle (the most recent 2 years), providing ground truth for climate models (which would in turn provide better characterization of past martian climates). An advantage of retrieving a sample of CO₂ ice is that it could be absolutely dated using carbon isotopes. Such a sample would need to remain frozen in order to preserve stratigraphy.

Small Sample from the Northern Residual Polar Cap:

A small (few cm³) sample of water ice from the surface of the northern residual polar cap would provide carbon and oxygen isotope and D/H ratios for the most recently deposited water ice. These isotope ratios could be analyzed in the laboratory to determine changes in water ice reservoirs, such as net flux into or out of the polar cap, atmosphere, or planet as a whole. These ratios could also be used for absolute dating by their link to known variations in solar activity. Analysis of grain size and porosity would lead to a better understanding of exactly how volatiles are deposited and accumulate at the poles, creating the largest surface water reservoirs on the planet. Dust entrained within the ice could also be characterized (volume percentage, composition, grain size, etc.) to understand its role in the mass balance and rheology of the polar deposits. Determination of composition would provide ground truth to orbital spectroscopic observations. One could also search for signs of alteration of dust grains (e.g., formation of sulfates) and of ice grain metamorphism. Such a complete understanding of even this small sample of polar ice would not only tell us a great deal about the martian water cycle, but it would

also provide engineering constraints for future larger-scale drilling missions to the poles. A sample that remains frozen would be ideal, but D/H and oxygen isotope ratios, as well as volume percentages and grain sizes of dust, could also be obtained from meltwater.

Short Ice Core Sample from the Northern Residual Polar Cap:

While not well-constrained, the average absolute accumulation rate of north polar volatiles over the last several hundred thousand years is estimated to be ~0.5 mm/yr. Thus, a very short core sample yields stratigraphic information covering many years (e.g., a minimum of 5 cm would span 100 years, allowing a link with Viking observations even if the topmost layer is 70 yrs old). The same types of analyses described above could be performed on a core sample containing many annual layers, leading to an invaluable record of the changes in composition, grain size, accumulation rate, etc., over time to annual or even seasonal precision. No other type of sample from anywhere on Mars would provide such a complete and accurate characterization of Mars' recent climate history. One sample from the pole would tell us about the history of the planet as whole, in terms of both surface and atmospheric water. Such a sample would clearly need to remain frozen.

Short Ice Core Sample from the Northern or Southern Polar Layered Deposits:

If a Mars sample return includes a rover, then a core sample (10 cm would cover ~200 years and would be of the layer thickness scale that HiRISE could observe, providing context) could be retrieved from an exposure of the polar layered deposits within a polar trough or scarp. On the polar plateaus, the areas between scarps and troughs are wide and flat, and the north polar troughs have walls whose maximum slopes are ~10°, well within the capability of current rovers. The polar layered deposits are older than the residual caps; thus, analyses similar to those described above would allow us to characterize the martian climate from hundreds of thousands of years into the past. A sample taken from the base of the north or south polar deposits exposed in one of the large chasmata would be composed of ice and other materials potentially millions of years old.

C. Objective: Characterize the State and Processes of the Martian Atmosphere of Critical Importance for the Safe Operation of Spacecraft (no priority order).

This objective focuses on atmospheric processes of importance for the safe implementation of spacecraft missions. These investigations would yield the critical information necessary to improve the likelihood of successful execution of missions in the Martian environment. Investigations would seek to characterize the atmosphere from the surface to 400 km altitude to support spacecraft landing, flight, aerocapture, aerobraking, long-term orbital stability, targeting of observations from orbit, and mission planning. Every effort should be made to accommodate instruments that address these investigations on each spacecraft bound for Mars.

Implications for sample return.

Discussion Leads: **Rob Manning** and **Walt Engelund**

Returned samples do not contribute to this objective. This statement applies to all four investigations under this objective.

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1. **Investigation:** Understand the thermal and dynamical behavior of the planetary boundary layer.
 2. **Investigation:** Understand and monitor the behavior of the lower atmosphere (0-80km) on synoptic scales.
 3. **Investigation:** Determine the atmospheric mass density and its variation over the 80 to 200 km altitude range.
 4. **Investigation:** Determine the atmospheric mass density and its variations at altitudes above 200 km.

III. GOAL: DETERMINE THE EVOLUTION OF THE SURFACE AND INTERIOR OF MARS

Insight into the composition, structure, and history of Mars is fundamental to understanding the solar system as a whole, as well as providing insight into the history and processes of our own planet. Thus there are compelling scientific motivations for the study of the surface and interior of the planet in its own right. The recent heightened interest in the possibility of life on Mars provides additional emphasis for these investigations. Geology informs virtually every aspect of the study of conditions conducive to the origin and persistence of life, and the study of the interior would provide important clues about a wide range of topics, including the early history of Mars, sources of volatiles, and geothermal energy.

The unique aspect of Mars, that in many ways makes it appear more Earth-like and sets it apart from the other planets, is evidence of the presence and activity of liquid water at or near the surface. This has enormous geological implications affecting, for example, erosion, weathering, heat flow, and the possibility of life (which can, in turn, have significant effects on geological processes). Thus, an emphasis on water is a logical framework within which to explore the planet.

A. Objective: Determine the nature and evolution of the geologic processes that have created and modified the Martian crust and surface (investigations in priority order)

The Martian surface contains the record of all the processes that shaped it, from initial differentiation to volcanism, to modification by impact, wind, and water. Understanding that record would help us understand the total inventory and role of water on Mars, regions likely to have been habitable to life, the processes involved in surface-atmosphere interactions, and the thermal history of the planet.

1. Investigation: Determine the present state, 3-dimensional distribution, and cycling of water on Mars.

Water is an important geologic material on Mars, influencing most geological processes including the formation of sedimentary, igneous and metamorphic rocks, the weathering of geological materials, and deformation of the lithosphere. Determining the distribution of water on Mars would require global observations using subsurface sounding and remote sensing, coupled with detailed local and regional sounding and measurements.

Water on Mars today is present in several forms potentially accessible by sample return: the atmosphere contains a trace amount of water that varies with season and location; the polar regions and pole-ward subsurface are inferred to contain water ice; and rocks and soils very likely contain water trapped in both relatively high temperature (“igneous” or “primary”) and low temperature (“sedimentary” or “alteration”) minerals. This would be a broad investigation intended to capture a current “snapshot” of water in various Martian reservoirs and to understand how these reservoirs interact. Quantitative analyses of Martian atmosphere, ices, regolith, and a variety of rocks would be required to address this investigation. The present state and information on the distribution of water could be determined through simple abundance determinations in different minerals, ices and gas samples, while isotopic ratios of hydrogen (D/H) and oxygen ($^{18}\text{O}/^{16}\text{O}$ and $^{17}\text{O}/^{16}\text{O}$) would provide key insights into the cycling of water.

The location of the landing site would profoundly affect the types of samples available to satisfy this goal. Latitude is the dominant control, but other geologic factors would determine the abundance of water in its various forms; ground ice is likely to be accessible pole-wards of ~55°; water of hydration is found heterogeneously at the MER landing sites; surface frost is found on pole-facing slopes; atmospheric water vapor is geographically and seasonally variable.

Because of the wide variety of likely water-hosts and the paucity of quantitative knowledge about the distribution and form of water on Mars, almost any samples collected by a Mars sample return could be of use in addressing this investigation. Specifically, samples collected to address Goal III investigations A-2 thru 6 and A-8 and 9 would all be very relevant to this investigation and the goals in these sections overlap the ones here.

Sample types needed. Samples from the atmosphere, regolith grains, and cores/small pebbles of sedimentary, altered, and igneous rocks would be needed.

Sample diversity needed. The greater the variety of samples, the more complete the “inventory” required for this investigation would be. Ice samples also would be desired, but would probably be beyond the scope of the first sample return mission.

Physical condition (rock, pulverized rock, etc.). Samples would include atmospheric, grains, and rock cores or small pebbles.

Contamination types and limits that affect this investigation. Samples should be separated to minimize reaction/interaction in the sample container.

Sample number and mass. At a minimum, significant progress on this investigation could be made with the following samples:

- (1) ~1 cc STP of atmosphere isolated from soil and rock samples
- (2) ~ 1 gram of regolith for mineralogical and isotopic studies of individual grains
- (3) Cores or small (several gram) pebbles of sedimentary/aqueously altered rocks for petrologic, geochemical and isotopic analysis
- (4) Cores or small (several gram) pebbles of igneous rocks for petrologic, geochemical and isotopic analysis

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Samples for this investigation should be collected in such a way as to preserve their mineralogic integrity as much as possible so that water could be attributed to specific minerals. In addition, the samples should be preserved at relatively low temperatures so as to not compromise their volatile content or form.

Maximum sample temperatures for sample integrity. Given the goal of characterizing water content of these samples, they should be kept at <0° C.

Impact of degradation on the investigation. Loss of volatile components in samples would diminish their value to this investigation.

Required/preferred sampling hardware. None identified.

Data needed for sample choice and in situ characterization. In order to translate the microscopic analyses of the rock samples to the “global” inventory sought in this investigation, some documentation that would allow the samples to be placed in their local and global context

is highly desirable. Therefore, samples of units either characterized by other missions (MER, MSL) or by in situ observations on a Mars sample return itself would be much more valuable than random or poorly documented samples.

Estimate of required mobility range. Not determined.

2. Investigation: Evaluate fluvial, subaqueous, pyroclastic, subaerial, and other sedimentary processes and their evolution and distribution through time, up to and including the present.

Locations with fluvial and lacustrine sediments are likely sites to detect traces of prebiotic compounds and evidence of life. Sediments also record the history of water processes on Mars. Polar layered terrains in particular may preserve a unique record of climate history. Aeolian sediments record a combination of globally averaged and locally derived fine-grained sediments and weathering products. Understanding sedimentary processes requires knowledge of the age, sequence, lithology, and composition of sedimentary rocks (including chemical deposits, such as those observed at Meridiani); the rates, durations, environmental conditions, and mechanics of weathering, cementation, and transport processes; and the fluvial and lacustrine record preserved in the morphology of the surface and shallow subsurface (e.g., beneath surficial deposits).

Orbital and in-situ investigations of sedimentary materials ultimately are limited by the scale and complexity of the desired measurements. Returned samples would greatly expand our understanding of the environments and processes that have led to the range of sedimentary materials evident at the Martian surface. The types of measurements that could be done on returned samples in the lab include:

- Grain size distribution: would allow assessment of the physical parameters of transport currents and sedimentation type, i.e., gravity vs. current driven processes, and different sedimentary environments from sorting characteristics
- Grain morphometry: the shape of the grain is indicative of velocity, rheology and duration of the sedimentary flow (i.e., aeolian sands show very smooth shape with characteristic impact marks)
- Microscopic studies of rock thin-sections: for clastic sediments this would help to understand the origin (provenance) of the grains as well as the composition of cements. For chemical sediments, it would aid in matrix vs. cement classification to understand the diagenetic processes of lithification including the environment conditions (e.g., arid vs. wet conditions, chemical characteristics, relative timing, selection of samples for dating sedimentary processes)
- Geochemical and stable isotopic studies at high resolution, using microanalytical methods to characterize sources and processes in both clastic and chemical sediments
- Isotopic dating of chemical precipitates, such as carbonate and sulfates, might also be accomplished if the correct samples are returned. This would provide the only direct and absolute temporal constraint on the timing of water-based chemical processes on the Martian surface. However, multiple isotopic systems yielding the same age would be required before the time of formation of the material could be known with confidence. Ar-Ar dating has been completed on terrestrial jarosite and might be a useful technique when applied to

Martian materials. However, the presence of atmospheric Ar adds complexity to the interpretation of these data and likely necessitates the use of additional chronometric systems such as Rb-Sr, Sm-Nd, or U-Th-Pb. In order to apply these isotopic systems, several minerals would be required that are: (1) derived from a common fluid with the same initial isotopic composition and (2) have different parent/daughter ratios within their structures. Potential sample sets that could be dated include jarosite-gypsum and calcite-siderite-magnesite. Individual samples containing multiple mineral phases or multiple samples derived from single evaporation/precipitation sequences would be required for dating.

The large variety of sedimentary deposits identified from orbit requires studies at the outcrop scale using high-resolution imaging and topographic analysis to recognize sedimentary structures from meter-scale to centimeter-scale. To select the appropriate samples for terrestrial studies, a survey from the landing site should be supported by high-resolution imaging (at mm scale) to identify any diagnostic sedimentary structures that are indicative of particular flow dynamics.

Experience from MER has demonstrated that sedimentary materials can include a complex mixture of siliciclastic components (derived from basalt with varying degrees of alteration leading to varying amounts of clays and amorphous secondary products) and chemical components (sulfates, chlorides, silica - state of crystallization unknown and likely variable, possibly carbonates, and no doubt some surprises). Such rocks typically have a complex diagenetic history that is preserved in the micro-textures and mineralogical compositions. Thus the challenge would be to preserve these features to the greatest degree possible in any returned samples.

Sedimentary materials, especially those that have experienced interaction with water, would be the target of other investigations. These include but are not limited to IA2, IB4, IC2, IC3, IIB4, and IIIA6.

Sample types needed. Sedimentary material from outcrop would be the ideal. Samples of float rocks that could be readily related to a stratigraphic section would be permissible.

Sample diversity needed. Stratigraphy can vary over scales of ~1 m to several meters depending on sedimentary environment. It would not be necessary that degree of induration be a major factor in sample selection, but it is recognized that there would be the need to cover the major lithologies and the diagenetic history to the greatest degree possible. As an example, we could take a section such as Meridiani and plan how it should be sampled. At Endurance/Eagle craters, about 8 samples would be a minimum to properly characterize the stratigraphic variability. This would include 3 samples of different facies and 2 extra samples to gauge the degree of stratigraphic variation in chemistry, an extra from the upper unit that has high grind energy (i.e., especially hard rock) and 2 samples from the diagenetic front at Whatanga contact. This emphasizes the importance of *in situ* measurements in preparation for sampling. This is also just an example. For a different depositional environment, the answer could be very different.

Physical condition (rock, pulverized rock, etc.). It would be advisable to collect a chunk of rock rather than small fragments to allow the reconstruction of the stratigraphy at microscopic scale from the thin-section. Core samples would be ideal.

Contamination types and limits that affect this investigation. For rocks, intact drill cores or sample chips, cross-contamination would not be a major problem for textural analysis if samples remain intact. For unconsolidated sediments, cross contamination would be an issue for textural

analysis and should be <2%. Cross-contamination levels of <1% (and preferably <0.1%) would be required for chemical and isotopic analyses on Earth. Capability would be needed to evaluate potential contamination through imaging of the entire sampling stream (e.g., drill, scoop, inlet).

Sample number and mass. As indicated above, to investigate even a few meters of stratigraphic section might require 5-10 samples. A rough estimate of the sample mass, considering the need for 1 cm on a side for the microscopic analysis, about 1 cm³ would be needed, if density ~3 g/cm³ then we should have ~3 g of sample. For unconsolidated sediments at least 1 cubic centimeter, depending on scale of bedding, textures anticipated and grain sizes. For age dating, because the abundances of Rb, Sr, Sm, Nd, U, Th, Pb, and even K are unknown in these minerals the amount of sample that would be required to complete these analyses is poorly constrained. Nevertheless, it seems likely that ages could be determined on samples of ~1-2 g mass.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Many sulfates are highly unstable and are likely to undergo phase transformations (e.g., dehydration) and mineralogical reactions (e.g., Fe-sulfate to Fe-oxides) if the ambient environment is not maintained.

Maximum sample temperatures for sample integrity. Given the susceptibility to phase changes of various sulfates, temperatures less than those experienced at the sampling site would be desired. This is likely to be ~0° C or less.

Impact of degradation on the investigation. Some phase transformations could result in major volume changes and thus could seriously disrupt the textures of the samples during collection and transport to Earth.

Required/preferred sampling hardware. Mineral structure and composition must be preserved during collection and transport. Sample storage in sealed containers to preserve any water released from dehydration reactions would be desired. Capability to rapidly transfer samples to storage containers, preferably autonomously within minutes but no longer than one communication cycle, would help ensure preservation of hydrated phases. Preferred capabilities would be to monitor and, if possible, control relative humidity and temperatures. The kinetics of sulfate dehydration and oxidation reactions should be evaluated, but it is expected that they may show rapid changes. For example diagenetically altered melanterite (in water) through the sequence schwertmannite – jarosite – goethite (-starting to form hematite) is known to form at room temperature in the space of a several weeks. So keeping samples at as low a temperature as possible would be a priority. However, if that is unrealistic, then the entire sample should be encapsulated and “put the pieces back together” on Earth.

Data needed for sample choice and in situ characterization. Context imaging on scales ranging from <20 microns (scale of microtextures) to about 2 m (scale of bedforms). The intent here would be to get as much *in situ* textural information as possible so that if the sample changes, its original character could be reconstructed. The preservation of textures would be a very high priority. In diagenetic studies, the textures provide the roadmap to the sequence of events that could then be analyzed using micro-sampling techniques.

Estimate of required mobility range. This would be landing site dependent, but the need to reach outcrop would be the most significant mobility requirement. Once at outcrop, mobility of <10 m probably would be sufficient.

3. **Investigation:** Calibrate the cratering record and absolute ages for Mars.

The evolution of the surface and interior of Mars, as well as the possible evolution of life, must be placed in an absolute timescale, which is presently lacking for Mars. Developing this chronology requires determining the absolute ages of geological units of known crater ages.

Returned samples of known geological context offer the only way to characterize the absolute chronology of Martian surfaces. Once the absolute age of a surface is known, then ideas of superposition and crater density could be used to infer relative ages of units on a more global scale (i.e., photogeologically). These sorts of calibrations could feed into life questions, i.e., Could life have developed during a heavy bombardment? Was there a heavy bombardment?

The choice of landing site would be of paramount importance to the success of this investigation. At a minimum, the landing site must be well characterized in terms of crater density. Given the abundant evidence for burial and exhumation in various locations across Mars, the geomorphic surface containing the landing site must have been continuously exposed to impacts throughout Martian history. Additionally, this surface must contain a rock unit exposed over a large enough area and emplaced over a short enough time period that it represents a distinct time horizon marking the zero age of the cratering history. Large flood basalts are an example. The surface must contain materials that could be dated by several radioactive age-dating methods including Rb-Sr, Sm-Nd, U-Pb, and Ar-Ar. Basalts and/or other igneous rocks could be dated using these techniques, and it would be important to apply multiple chronometers to each sample, because concordant ages are considered more robust. Among Martian meteorite studies, it is not uncommon for a particular isotopic system to be disturbed while other system(s) are not. These disturbances can often result from varying degrees of thermal metamorphism associated with shock or are due to alteration on Mars. By applying multiple chronometers it would be possible to obtain absolute crystallization ages, metamorphic overprint ages, and possibly the timing of any aqueous alteration present in the igneous rocks.

The need for igneous rock samples overlaps with investigation IIIA4 and the requirement that they come from large-scale crustal units would satisfy one of the requirements from IIIA6. This investigation also is closely linked to IIIA11 concerning the effect of impacts on the evolution of the Martian crust.

Sample types needed. Individual samples must be relatable to cratered surfaces in order to calibrate cratering rates. This could be accomplished by directly sampling outcrop, or from float rocks by identifying unique mineralogical/geochemical characteristics in the rock and relating it to localized bedrock.

Sample diversity needed. Ideally, cratering rates would be best determined if at least 3 surfaces representing young, medium, and old terrain were sampled.

Physical condition (rock, pulverized rock, etc.). Rock, core, or chips would be appropriate for this investigation.

Contamination types and limits that affect this investigation. Samples for chronometry would not need to be isolated from other samples nor packaged separately.

Sample number and mass. Two samples from any available time stratigraphic surface would insure that the best dates could be obtained and maximize the probability that ages could be

determined on any given surface. The basic petrography of the sample must be determined in order to confirm that the sample is igneous, homogeneous, and likely to be in isotopic equilibrium. This would require enough mass for a thin section to be made. The absolute minimum sample requirements would be on the order of ~300 mg/sample assuming a depleted composition; slightly less sample could be used if samples are more enriched. However, more sample would be required if the sample is dominated by one mineral or contains large amounts of impact melt.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). None identified.

Maximum sample temperatures for sample integrity. Temperature excursions to ~50°C (during Earth re-entry if return canister is not refrigerated) would not be a concern for these studies.

Impact of degradation on the investigation. None identified.

Required/preferred sampling hardware. No specific requirements.

Data needed for sample choice and in situ characterization. Sufficient information to demonstrate igneous origin.

Estimate of required mobility range. With the proper landing site, it might be possible to find surfaces of significantly different ages within a few kilometers of each other or perhaps less. A single age probably could be sampled with little to no mobility at the right site.

4. Investigation: Evaluate igneous processes and their evolution through time, including the present.

This investigation covers the broad range of igneous processes including, for example, volcanic outgassing and volatile evolution. In addition to dramatically molding the surface of the planet, volcanic processes are the primary mechanism for release of water and atmospheric gasses that support potential past and present life and human exploration. Sites of present day volcanism, if any, might be prime sites to investigate for life. This investigation would require global imaging at a range of wavelengths, geologic mapping, in-situ and remote techniques for distinguishing igneous and sedimentary rocks, evaluation of current activity.

Igneous samples returned from the surface of Mars could be used to address various aspects of Martian magmatism including magmatic differentiation, volatile outgassing, composition and evolution. Knowledge gained from the analysis of these samples potentially could be extended to other parts of Mars via orbital remote sensing.

Sample diversity would be critical in allowing interpretation of magmatic differentiation. Specifically, if a differentiation sequence is collected, knowledge of temperature, pressure, and oxygen fugacity could be derived from detailed geochemical studies of samples. The Mars Exploration Rover Spirit has identified a set of rocks that appear to be part of an alkaline differentiation trend. But the limited analytical capability of its payload leaves many unanswered questions. Returned samples would allow a more robust and complete understanding of such trends. In addition, many volcanic rocks may contain xenoliths from other parts of the magmatic complex, or from the mantle source from which they were derived. Identification and collection of such materials would greatly enhance our understanding of magmatic processes operating at a given site.

Collection of regolith would offer a diversity of clast types from different localities, some potentially hundreds of kilometers away. The utility of this approach is shown by detailed studies of Apollo 16 clasts from a breccia that have led to a greater understanding of the magmatic and volcanic processes in a large region of the Moon. Shock pressure could of course transform the original igneous mineralogy of some exogenous samples, as it has in some Martian meteorites (e.g., plagioclase has transformed to maskelynite glass), but igneous petrogenesis could be unraveled despite this effect.

Volatile composition could be addressed with a multitude of approaches using returned samples of primary unaltered igneous rocks. Small melt inclusions in volcanic phenocrysts contain trapped magmatic volatiles that could be measured using a variety of micro-techniques such as SIMS and FTIR. The amount and nature of C, S, O and H associated with any magmatic system could be evaluated using these inclusions, which are also common in Martian meteorites. Any preserved volcanic glass could lead to information about S and O (microprobe and Mössbauer measurements), and H measurements in minerals such as olivine or pyroxene (FTIR measurement) could provide information about OH or H₂O in Martian magma chambers or source regions (mantle).

Outgassing processes could be understood with studies of vesicle size and distribution, which could be studied using non-destructive 3D imaging techniques such as micro-tomography at a synchrotron facility. Such approaches have yielded much useful data about basaltic volcanism on asteroids and the Moon. In addition, minerals formed by sublimation at volcanic areas could give insight into nature of fluids (chlorides, sulfates, oxides), just as they do on Earth, and could be studied using a wide variety of analytical techniques including x-ray diffraction, raman and infrared spectroscopy, SEM, SIMS, and electron microprobe analysis.

The evolution of volatiles in the Martian crust and mantle could be known from isotopic and trace element studies of all samples collected: classic Ar-Ar, Rb-Sr, Sm-Nd, and Lu-Hf would all be possible with standard mass spectrometry techniques, and many key trace elements (rare earth elements or REE, siderophile elements, volatile elements, and chalcophile elements) could provide information about the Martian interior, while providing links to volatiles. For small samples, where not enough material is present to use a classical approach, ion microprobe dating and characterization would be possible (albeit with lower precision, but yielding nonetheless useful ages) on very small igneous rocks, and could even broaden the number of systems possible to include systems such as Re-Os (normally more mass intensive).

The collection of igneous rock samples for this investigation overlaps with investigation IIIA3 and IIIA6.

Sample types needed. Martian magmatism could be studied, with an emphasis on evolution through time, using several different kinds of returned samples – large samples collected in place (5 to 10 g of igneous rock), would allow application of several different isotope chronometers, but even relatively small regolith samples (0.5 to 1 g) could include some exogenous rocks that would provide information about regional magmatism.

Sample diversity needed. In order to document possible magmatic trends, at least three samples of different composition are desired.

Physical condition (rock, pulverized rock, etc.). Cores, rocks, or chips, either from outcrop or exogenous materials would constitute good samples for this investigation.

Contamination types and limits that affect this investigation. Cross contamination levels of < 1% (and preferably < 0.1%) would be required for chemical and isotopic analyses in Earth labs).

Sample number and mass. At least three samples are desired. Mass estimates for magmatism studies could draw on the experience of studying a small Martian meteorite, such as QUE 94201. Allocation of ~ 2 g of material to various investigators allowed a determination of its age, and bulk elemental and isotopic composition. Utilization of a 1 g chip of this meteorite to make 5 thin sections allowed a great diversity of scientific problems to be addressed by 14 investigators. This experience has guided us in making mass estimates for this investigation in Table 1.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Not identified.

Maximum sample temperatures for sample integrity. The momentary heating to 50 °C upon entry into Earth’s atmosphere would not pose a problem unless volcanic sublimates breakdown and release water or other volatiles into the sample chamber affecting other samples. However, heating above 500 °C (as per possible planetary protection requirements) could cause the breakdown of volcanic sublimates and/or compromise the integrity of volatiles trapped in melt inclusions; a less invasive sterilization technique would be preferred.

Impact of degradation on the investigation. Not identified.

Required/preferred sampling hardware. A coring device would provide ideal samples.

Data needed for sample choice and in situ characterization. Context imaging on scales ranging from 1 mm to about 2 m in order to sample vertically on lava or pyroclastic flows to maximize diversity. Capability would be needed to evaluate potential contamination through imaging of the entire sampling stream (e.g., scoop, drill, inlet, etc.).

Estimate of required mobility range. With the likelihood of encountering exogenous rocks over relatively short distances, a range of a few km’s would be sufficient.

Additional comments.

Table 1: Summary of processes, samples, mass required, and techniques (thin section uses 1 g)

<i>Process</i>	<i>Sample type</i>	<i>technique</i>	<i>Min. mass (g)</i>	<i>Element, isotope, or mineral</i>
1) Magmatic differentiation	Rock	Mass spectrometry (TIMS, ICP)	0.5	Major elements, REE, MSE, HSE, lithophile, chalcophile elements
	Thin section	Laser ablation, SIMS, XANES	-	Major and trace, oxidation state
2) Volatile composition	Rock	Mossbauer, TEM	0.2	oxidation state, ferromagnesian minerals
	Thin section	SIMS, FTIR, EMPA	-	S, C, O, H, N, F, Cl, Br
3) Outgassing	Rock	Raman, xrd, SEM, tomography	0.5	Sulfates, sulfides, phosphates, hydroxides, oxides, carbonates
	Thin section	SEM, SIMS, FTIR, EMPA, crystal size distribution (CSD)	-	S, C, O, H, N, F, Cl, Br
4) Evolution	Rock	TIMS	1.0	Ar-Ar, Rb-Sr, Sm-Nd, Lu-Hf
	Thin section	SIMS	-	Rb-Sr, Sm-Nd, Lu-Hf, Re-Os

5. Investigation: Characterize surface-atmosphere interactions on Mars, including polar, Aeolian, chemical, weathering, mass-wasting and other processes.

The focus of this investigation is on processes that have operated for the last million years as recorded in the upper 1 m to 1 km of Mars. Understanding present geologic, hydrologic, and atmospheric processes is the key to understanding past environments and possible locations for near-surface water. Knowing the morphology, chemistry and mineralogy of both near surface rocks and alteration products is essential for calibrating remote sensing data. This study also has strong implications for resources and hazards for future human exploration. It would require orbital and surface-based remote sensing of the surface and shallow subsurface (meters to 10s of meters), and direct measurements of sediments and atmospheric boundary layer processes.

Physical processes related to surface-atmosphere interaction that have operated on time scales of $\sim 10^6$ years will be dominated by aeolian transport, with deposits resulting from recent mass-wasting and impact processes being potential but unlikely features observable at landing sites. Aeolian dust (suspension load) would be sampled for a variety of purposes but there is also potential for sampling active or inactive dunes and ripples (saltation, rolling loads). Both MER locations contain aeolian bedforms of interest to this investigation. Ripples were observed with a single-layer, coarse-grained lag that appears to armor the underlying finer-grained sand/silt particles. Samples obtained from such bedforms might offer clues to recent climate change on Mars.

Obliquity variation on timescales of $\sim 10^6$ years could result in transport of water from polar regions to mid- to low-latitudes via sublimation and precipitation and thus to a potential landing site. This in turn, could play a role in recent aqueous alteration or chemical/mineralogical remobilization on rock and grain surfaces. Chemical processes that have affected the Martian surface on time scales of $\sim 10^6$ years will influence samples to very shallow depths and would be difficult to distinguish from processes operating over much longer time scales (up to $\sim 10^9$ years). The best examples to draw from with the MER experience are the mm-scale alteration profiles found on all rock surfaces and mm-scale cemented zones at the surfaces of ripples and dunes. Such materials would include a variety of highly labile secondary minerals (clays, sulfates, chlorides). Interpreting such materials would require both chemical and textural information. The likely presence of highly reactive sulfate and chloride minerals may also result in hydration state profiles on surfaces of rocks, soils and aeolian features that, in turn, would reflect recent surface-atmosphere interaction. Finally, the identification of possible superoxides in the Martian soil would be an important objective of this investigation, although difficult to preserve in a returned sample.

Accordingly, the challenge for sampling would be to preserve primary mineralogy, chemistry, and textural relationships during sampling, storage and transport to Earth. If sample integrity could not be guaranteed, it would be necessary to characterize samples on the Martian surface to the greatest degree possible so that changes could be evaluated and to preserve all components of the original sample.

Many of the goals of addressing this investigation would also be relevant to addressing Goal III investigations A1, A2, A9 and perhaps A8 (and no doubt others). These sections should be coordinated to ensure that mutually exclusive requirements are not mandated. Any liquid water or ice that might be encountered would also play a role in interpreting recent surface-atmosphere

interaction and sampling approaches designed for other purposes (i.e., A1) should be adequate to address this investigation.

Sample types needed. The types of samples that would be needed include grains of various sizes and rock cores.

Sample diversity needed. An ideal set of samples would include dust, grains from aeolian bedforms, rock cores/chips with alteration rinds, and regolith.

Physical condition (rock, pulverized rock, etc.). For rock surfaces, one intact drill core sample to at least 1 cm depth for each surface profile studied. For cemented surfaces of unconsolidated deposits, ability to sample top 1 cm of deposit is desired. Preferred capability would be to keep profile intact, otherwise, it would require two samples (one surface, one interior) to characterize profile.

Contamination types and limits that affect this investigation. Cross-contamination levels of <1% (and preferably <0.1%) would be required for chemical and isotopic analyses on Earth. Capability would be needed to evaluate potential contamination through imaging of the entire sampling stream (e.g., drill, scoop, inlet).

Sample number and mass. In order to characterize and interpret the physical processes of young aeolian ripples and dunes (e.g., grain size distribution, grain shape) the requirements would be as follows:

1. For grain size analysis, minimum sample sizes of ~1 g (equivalent to several hundred sand grains 1mm in diameter) and perhaps greater (up to ~10 g) depending on grain size;
2. Three samples would be preferred to characterize a single ripple (dune) consisting of leeward, windward and interior.

For regolith material, a sample from the surface and one or more within a trench would be ideal. For weathered rocks, one core that includes the outer surface would be a minimum requirement. A single sample of dust would be sufficient.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). There is a range of vulnerability to degradation among the different sample types. For the most vulnerable samples, we recommend:

1. Sample storage in sealed containers to preserve any water released from dehydration reactions.
2. Preferred capabilities would be to monitor and, if possible, control relative humidity and temperatures.

Maximum sample temperatures for sample integrity. The key requirement for preserving the chemical nature of the soil surfaces to the extent possible would be to keep the sample at low temperature, i.e., at Mars-ambient temperature or ideally colder.

Impact of degradation on the investigation. The impact ranges from severe for the investigation of superoxides to modest for characterizing aeolian sediments.

Required/preferred sampling hardware.

1. Coring would be required for sampling of rocks.

2. Capability to rapidly transfer samples to storage containers; preferably autonomously within minutes but no longer than one communication cycle.
3. Preferred capability would be for trenching to depths of >10 cm to access subsurface material with the ability to preserve the trench wall undisturbed.

Data needed for sample choice and in situ characterization. Context imaging on scales of ~100 μm (intact sample prior to storage) to ~2 m (size of rock/outcrop). Similar context imaging would be required for aeolian samples

Estimate of required mobility range. Based on MER experience, probably <1 km for all materials of interest.

6. Investigation: 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.

The vertical and global variation of rock properties and composition record formative events in the planet's early history, constrain the distribution of subsurface aquifers, and aid interpretation of past igneous and sedimentary processes. Determining these structures requires global and local remote sensing and deeper subsurface sounding (100s of meters to kilometers), detailed geologic mapping, and determination of mineralogy and composition of surface material.

The large-scale crustal units of Mars have been identified based on information obtained from orbital and in some cases, telescopic data sets. The hemispheric dichotomy and other more regional-scale variations of the crust are recognized by a combination of topographic, morphologic, spectral, magnetic, and gravity attributes. Vertical variations of the crust are poorly constrained but are evident in the layering visible in the walls of the Valles Marineris and suggested by the presence of lateral heterogeneities of surface attributes. The best way to ensure that returned samples serve as "ground truth" for large-scale crustal units would be to collect samples that could be related to observations made from orbit. At a minimum, samples must be understood within the geologic context of the landing site from which they are collected. Although a diverse set of samples is desirable, with respect to the investigation of regional/global-scale features of the crust, samples with no clear provenance would be best avoided.

On the surface, identifying samples representative of large-scale crustal units would in some cases be straightforward and in others, more challenging. At a given landing site, the potential exists to encounter rocks that represent both local and regional geologic units. For example, the sedimentary rocks of the Home Plate feature in Gusev Crater appear highly localized, while the olivine-rich basalts of the plains are more regionally significant. The former supply information about a small-scale addition to the crust, while the latter are probably representative of large-scale contributions found elsewhere across the planet. Both rock units are readily distinguishable on the ground and from orbit. This is not the case with other rocks encountered by the Spirit rover. In the Columbia Hills at least three varieties of basalts were discovered, including plains basalt, based on their spectral characteristics. All three are visually similar yet only the plains basalt appears to represent a major component of Gusev Crater. Had the rover only traversed the Columbia Hills, it would have been unclear which of the three basalt types was regionally significant. This example demonstrates the need for a carefully chosen landing site, mobility,

and some means of characterizing rocks prior to selection in order for returned samples to be placed into a larger context.

Samples collected for this investigation would most likely to be volcanic igneous rocks but sedimentary rocks that encompass large-scale regional deposits are desirable. This set of samples overlaps with those from investigations IIIA2-4.

Sample types needed. Orbital instruments have revealed a range of spectrally distinct crustal units that are the result of mineralogic diversity. Rock samples representative of the various spectral “types” and igneous minerals observed from orbit would be most appropriate for this investigation.

Sample diversity needed. Because of the emphasis in this investigation on large-scale crustal units, it is unlikely that a given landing site would contain more than one or two rock types that fit the criteria. However, there exists the possibility of exogenous samples representing other crustal units that have been lofted into place by impact processes that might be available at a given landing site.

Physical condition (rock, pulverized rock, etc.). Because they would serve as ground truth for orbital spectral measurements, consideration must be given to what constitutes an ideal sample for laboratory spectral measurements. Cores or chips that preserve some of the natural surface of the original rock would be required.

Contamination types and limits that affect this investigation. Bulk mineral and chemical measurements would be the first priority for these samples. Consequently, the main science goal (ground truth) would not be significantly impacted by minor contamination.

Sample number and mass. Two samples from each representative crustal unit, each with a mass of at least 1g would be ideal.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Igneous samples would be less susceptible to degradation than possible sedimentary samples.

Maximum sample temperatures for sample integrity. The possibility of hydrated alteration minerals to be present on/in the samples would require maintaining temperatures to <50° C.

Impact of degradation on the investigation. Probably low.

Required/preferred sampling hardware. To achieve the objectives of this investigation, some form of instrumentation would be required that can characterize 10s to 100s of rocks along a traverse. The analytic capability would need to be at the scale of the samples to be collected. Not only would such instrumentation ensure a diversity of samples, but it would also form the basis for establishing the provenance of a given sample. Once identified, coring of outcrop or large float rocks would be ideal.

Data needed for sample choice and in situ characterization. VNIR and/or TIR spectra would best serve the objective of identifying samples that are representative of large-scale crustal units.

Estimate of required mobility range. Both Gusev crater and Meridiani Planum sites demonstrate that rocks representing large-scale units were readily available within several meters of the lander. Accessing a greater diversity of samples might require several km of driving.

7. Investigation: Document the tectonic history of the Martian crust, including present activity.

Understanding the tectonic record is crucial for understanding the geologic history as well as the temporal evolution of internal processes. This, in turn, places constraints on release of volatiles from differentiation and volcanic activity and the effect of tectonic structures (faults and fractures in particular) on subsurface hydrology. This investigation requires geologic mapping using high resolution topographic data combined with high-resolution images at a range of wavelengths, magnetic and gravity data, and seismic monitoring.

No perceived relevance to sample return.

8. Investigation: Evaluate the distribution and intensity of hydrothermal processes through time, up to and including the present.

Hydrothermal systems are thought to be connected with the earliest evolution of life on the Earth. Hydrothermal systems may also play an important role in the chemical and isotopic evolution of the atmosphere, and the formation of the Martian regolith. Deposits from hydrothermal systems have the potential to record the history of the biosphere and crust-atmosphere interactions throughout Martian history. Assessing hydrothermal processes requires knowledge of the age and duration of the hydrothermal system, the heat source, and the isotopic and trace element chemistry and mineralogy of the materials deposited.

Beginning with the identification of aqueously derived mineral phases in Martian meteorites and now extending to identifications made by orbiting and rover-based instruments, the concept of aqueous alteration on Mars is well supported. However, in the case of the various sulfate, phyllosilicate, hematite, and goethite phases identified at Mars, the potential role of hydrothermal processes in their formation must be further investigated. Returned samples would allow detailed analyses that could not be done by landed missions alone. Fluid chemistry, temperature and atmospheric pCO₂ or pSO₂ conditions could be established. Radiometric age dating on secondary assemblages (e.g., Rb-Sr and K-Ar have been used successfully) would determine the age of hydrothermal alteration events and aqueous precipitation in the Mars geological history. Stable isotope analysis (e.g., C, N, O) would be necessary in order to constrain fluid temperatures associated with the secondary mineral formation. It would also help to reveal the isotopic composition of the atmosphere and crustal isotopic reservoirs at the time at which they formed. This, in turn, would provide constraints on past atmospheric thickness, composition and loss. For instance, heavy stable isotope compositions (e.g., ¹³C, D/H) in Martian meteorites are probably a result of impact induced atmospheric loss and sputtering from the early Mars atmosphere.

The discovery of an opaline silica deposit by the *Spirit* rover at Home Plate appears consistent with an ancient hydrothermal system probably arising from the interaction of magma with near-surface water or ice. This may represent the first intact hydrothermal system discovered on Mars and perhaps demonstrates what can be expected for the surface expression of some forms of hydrothermal alteration. No obvious indication of clay minerals or carbonates has been observed in the silica deposits. However, at least three of the 4-7 localities on Mars from which the Martian meteorites were derived contain carbonate at up to 1 vol. %. This carbonate – together with co-existing smectite clay and salts – has been used to constrain the temperature,

composition and duration of fluids from which these secondary mineral assemblages formed. There is a general consensus that they were precipitated relatively rapidly at $<150^{\circ}\text{C}$ from CO_2 -charged, brine-like fluids. The volume of carbonate could be used to constrain the partial pressure of CO_2 that the fluid equilibrated with in a near-surface setting. Heat sources for the fluids may include impact or local volcanism. However their origin is clearly decoupled from the igneous crystallization of the rocks from which the meteorites were ultimately formed. Returning carbonate, salt, clay-bearing or silica samples would be the best way to establish the environment in which these deposits formed.

The samples collected for this investigation most directly overlap with investigations outlined in Goal I. Martian materials that have experienced hydrothermal alteration, or more importantly, formed in a hydrothermal environment, would be good candidates for any investigation focused on addressing questions about habitability and life on Mars.

Sample types needed. Aqueous alteration is likely to be present in variety of different rock types on Mars. The igneous rocks in the Martian meteorites and the basalts of the *Spirit* site show significant secondary alteration. The sedimentary rocks at *Opportunity* show higher volumes of sulfate and hematite in some of their outcrops. Thus soil and igneous or sedimentary rocks may all contain secondary minerals formed in different ways: hydrothermal veins of silica, weathering of igneous minerals, evaporation of brines, deposition from standing water.

Sample diversity needed. See previous description.

Physical condition (rock, pulverized rock, etc.). Chips or cores that preserve original rock surfaces and possible veins would be important for investigating alteration.

Sample number and mass. The number of samples would be dependent on what is available at the landing site. Preparation of polished surfaces for compositional and textural analyses would require less than half-gram sized pieces

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Some of the hydrated sulfate minerals identified by the MER landers are only stable at $<0^{\circ}\text{C}$. For example, $\text{MgSO}_4 \cdot 11\text{H}_2\text{O}$ (soon to be officially called meridianiite) can change to the more common mineral epsomite at only 2°C . This phase change also results in the release of $\sim 30\%$ water by volume which could alter other water analyses. Silica materials also may be hydrated, although probably are less sensitive to dehydration than the sulfates. Release of water from some minerals could cause efflorescence and recrystallization of a variety of salt minerals particularly the highly soluble sulfate minerals. Clay minerals obviously are also sensitive to environmental conditions and ideally would be encapsulated in a way that preserves their hydration state: this means ensuring that smectite-like clays such as those identified at Marwth Vallis would be kept below 100°C , at which temperature they irreversibly dehydrate. Temperature control would be necessary if we wish to preserve the original mineralogy of the Mars samples.

Maximum sample temperatures for sample integrity. See previous description.

Impact of degradation on the investigation. See Vulnerability description.

Required/preferred sampling hardware. Coring would produce ideal samples in which exterior surfaces and interior textures are preserved.

Data needed for sample choice and in situ characterization. Some means of establishing whether a given rock or soil contains candidate hydrothermal phases would be needed.

Estimate of required mobility range. As shown by the *Spirit* example in Gusev crater, several km of traverse might be required to encounter clear examples of hydrothermal alteration.

9. Investigation: Determine the processes of regolith formation and subsequent modification, including weathering and diagenetic processes.

The regolith is a filter through which we view most of the Martian surface by remote sensing. In addition, it may provide a valuable record of the history of surface conditions and processes. Understanding regolith formation and modification requires quantitative measurement of mineralogy, chemistry, and physical parameters of the surface and shallow subsurface.

The regolith has proven to be among the most mineralogically, chemically and physically complex geological units encountered on Mars. Physical processes are likely dominated by aeolian transport and impact, but in places could also involve other mechanisms such as fluvial and glacial transport. Soil samples, from the uppermost part of the regolith, would provide a mixture of dust, sand and gravel-sized material. Coarse materials would provide access to locally derived components while the finer materials would be expected to be more representative of a global sampling.

The regolith at the visited landing sites appears to contain components that are broadly homogeneous but most sites also possess distinctive characteristics suggesting multiple sources. Thus the Meridiani regolith contains hematite spherules from the underlying bedrock, Pathfinder regolith contains components of the local K-rich rocks, and in places Columbia Hills regolith exhibits the P-rich characteristics of surrounding rocks. There is likely a meteoritic component averaging on the order of 2%. The regolith is enriched in S and Cl and in some places highly enriched in these elements. Sulfate mineralogy is complex and may involve a variety of post-depositional mineral transformations (e.g., involving ferric sulfates), constraining atmosphere-surface interactions. High silica deposits (most likely opaline silica) have also been found. Accordingly, sampling regolith must preserve material that could be used to address questions relating to primary depositional processes, primary mineralogy, and complex post-depositional aqueous processes that likely range from low-temperature (i.e., cryogenic) through to hydrothermal conditions (see also A8). The oxidation state, water content and pH of the current uppermost regolith or soil could also be determined, constraining mineral stability.

Although regoliths are complex, sampling issues are not dissimilar to a number of other investigations. Sufficient sample must be collected and preserved in a manner that would allow an evaluation of a variety of physical processes (e.g., grain size distributions) as well as the identification and characterization (chemically and isotopically) of complex mineralogy. Important textural information would likely be present on scales larger than sampling scales (centimeter to meter) and so sample sites would need to be characterized to the greatest degree possible.

Sample types needed. Regolith grain samples would be needed for this investigation.

Sample diversity needed. Regolith samples from any compositionally distinct units would be desired.

Physical condition (rock, pulverized rock, etc.). Regolith samples would be needed at various grain sizes.

Contamination types and limits that affect this investigation. Cross-contamination levels of <1% (and preferably <0.1%) would be required for chemical and isotopic analyses on Earth. Capability would be needed to evaluate potential contamination through imaging of the entire sampling stream (e.g., drill, scoop, inlet).

Sample number and mass.

1. Using the Columbia Hills as an example, it would be necessary to examine at least 2 regolith profiles in the vicinity of the landing site. For homogeneous regolith, at least 2 samples would be required (surface and at depth); for complex soils at least 3 samples and perhaps as many as 4-5 would be required to characterize regolith (e.g., surface, each visually distinctive zone within profile).
2. Scale of distinctive zones may be as fine as cm-scale requiring comparable scale for sampling. Sample sizes should be at least 1 cm³ in size.

Vulnerability of samples to degradation effects (T, volatile loss, etc.).

1. Sample storage in sealed containers to preserve any water released from dehydration reactions.
2. Preferred capabilities would be to monitor and, if possible, control relative humidity and temperatures. For instance, preservation of sulfates during sample return for subsequent mineralogical study would require temperature control <2° C and low humidity to inhibit efflorescence of the most soluble minerals.

Maximum sample temperatures for sample integrity. See above.

Impact of degradation on the investigation. See above.

Required/preferred sampling hardware.

1. Ability to carry out trenching on a scale comparable to MER would be required in order to expose soil profiles to scales on the order of decimeter. Deeper penetration of trenches is desirable.
2. Capability to rapidly transfer samples to storage containers; preferably autonomously within minutes but no longer than one communication cycle.

Data needed for sample choice and in situ characterization. Context imaging would be needed on scales of ~100 μm (grain to grain relationships of soils) to ~50 cm (upper limit on depth of trench).

Estimate of required mobility range. Based on all previous landed missions, regolith material would be readily available surrounding the lander.

Additional comments. Determination of the volatile and ice content of the regolith sample would be used to calculate a global inventory of CO₂ and H₂O that is currently trapped as ice or clathrate in the regolith. If the samples' temperature and humidity could be preserved during sample return then the identification of clathrates and ice could be attempted. These, together with hydrated minerals, are the two types of structure that are likely to currently trap volatiles in the Mars regolith (see also A5).

10. Investigation: Determine the nature of crustal magnetization and its origin.

The magnetization of the Martian crust is poorly understood, but is intimately related to the igneous, thermal, tectonic and hydrologic history of the crust. Addressing this problem requires high-resolution mapping of the magnetic field and knowledge of the mineralogy and magnetization of the surface.

When magnetic minerals form or deposit in presence of a magnetic field, they tend to align themselves in the direction of the magnetic north pole and become magnetized with a magnitude that scales with the field intensity [1]. Therefore paleomagnetic studies of rocks yield two main pieces of information: the *direction* and the *intensity* of ancient fields. Paleo-directional data could be used for at least three very important investigations: 1) determining if ancient magnetic fields were due to impact processes or a core dynamo, 2) characterizing the temporal behavior of the Martian paleofield (reversal frequency and secular variation) and 3) chronicling local and planetary tectonic evolution (motion of the crust and/or mantle with respect to the background field). Paleo-intensity studies of returned samples could provide a wealth of information concerning the cooling history of the planet by monitoring the strength of the Martian dynamo versus time. This information could be used to determine when the planet had a dynamo and when it decayed, which would give information about the mechanism generating the dynamo and thermal evolution of the planet. A strong ancient dynamo may have also provided protection from solar wind destruction of the Martian atmosphere and radiation protection for any primitive forms of life.

Because the original orientations of Martian meteorites on Mars are unknown, all paleomagnetic studies to date have only been able to measure the paleo-intensity of the Martian field. *In situ paleomagnetic studies of Mars bedrock and analysis of returned Martian samples would afford the advantage of knowing the geologic context of the samples but just as importantly, would provide the first opportunity to get paleo-directional information on Martian fields.*

As measured from Mars orbit, the current Martian magnetic field is rather weak, but the discovery of intense magnetic anomalies in the ancient southern cratered terrain and weaker anomalies even underlying the North Polar Basin by the Mars Global Surveyor mission provides strong evidence for an internal Martian dynamo acting during Noachian time [2]. These Martian magnetic anomalies are easily an order of magnitude stronger than their terrestrial counterparts; downward continuation of the spacecraft observations implies that local magnetic fields in many places on the surface of Mars are of comparable magnitude to that on Earth. These magnetic anomalies are intense enough to deflect and focus incoming radiation, so knowledge of their distribution and pattern would be extraordinarily important for locating possible future human settlements.

This investigation is strongly connected to investigations in Goal III, Objective B: Characterize the structure, composition dynamics and evolution of Mars' interior.

Sample types needed. The ideal samples for paleomagnetic investigations would be basalts from outcrops because of their high magnetization intensity, excellent fidelity for recording paleodirectional and paleointensity information, and the simple process by which they become magnetized. Sediments (both siliclastic and chemical) would also be useful for paleomagnetic studies, but they are less ideal because of their relatively weaker magnetization, tendency to record a magnetization direction shallower than the true direction (particularly for claystones),

and the lack of robust absolute paleointensity techniques for sediments. For either rock type, the samples should be collected from units with identifiable stratigraphy, layering, or other paleo-direction indicators, if possible. This would greatly facilitate determining how the orientation of the unit has changed since the time of magnetization.

Sample diversity needed. The choice of the landing site would be critical. Impact melts and regions heated by impacts should be avoided because they would likely have been demagnetized or remagnetized by impact processes (which may generate strong fields [4]). The samples ideally should be unshocked and unweathered. Potentially interesting sites would be the high crustal magnetic anomaly localities and bedrock outcrops at Meridiani and Gusev.

Physical condition (rock, pulverized rock, etc.). Core samples would be ideal.

Contamination types and limits that affect this investigation. See Vulnerability.

Sample number and mass. It would be advisable to collect multiple samples from each stratigraphic level with a coring device, or a long core that samples across stratigraphic sequences. This is done so that the samples could be averaged together and statistical analysis could be used. Using a coring unit ensures that orientation could be reconstructed in the laboratory. Assuming the samples are basalt, a minimum mass of 0.03 cm^3 per sample would be measurable with modern superconducting rock magnetometers. Sedimentary samples might require one or more orders of magnitude more sample mass (depending on the lithology).

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Samples should not be exposed to magnetic fields greater ~ 100 and ideally no greater than $\sim 1 \text{ G}$. The latter requirement could be easily fulfilled if the samples are shielded inside of a high magnetic permeability container for the return trip to Earth.

Maximum sample temperatures for sample integrity. Samples ideally should not be heated above ambient Martian temperatures.

Required/preferred sampling hardware. The drill used to collect the cores ideally should be made from nonmagnetic materials to avoid contaminating weakly magnetized rocks. To determine the direction of the paleomagnetic field the samples should be orientated with respect to present true north and vertical before they are removed from the outcrop. This was done on the Apollo missions by photographing the sample in the same field of view as a gnomon. A gnomon is a tripod and sun compass with a freely rotating gimbaled vertical bar that always points toward true vertical (such that sample inclination can be inferred) and whose shadow can be used for obtaining geographic declination [5]. This could also probably be done with a combination of imagery and orientation data from a rover arm.

Data needed for sample choice and in situ characterization. See previous description.

Estimate of required mobility range. Given the need for samples from outcrop, the MER experience demonstrates that depending on landing site, outcrops would be within several meters to several km of the lander.

Additional comments. References:

[1] R.F. Butler, Paleomagnetism: magnetic domains to geologic terranes, Blackwell Scientific Publications, Boston, 1992, 319 pp.

- [2] M. Acuna, J. Connerney, P. Wasilewski, C. Mazelle, J. Sauvaud, D. Vignes, C. d'Uston, H. Reme, R. Lin, D. Mitchell, J. McFadden, D. Curtis, P. Cloutier, S. Bauer, MGS magnetic fields and electron reflectometer investigation: Discovery of paleomagnetic fields due to crustal remanence, *Moon and Mars* 23(1999) 1879-1886.
- [3] J.H. Allton, *Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers*, National Aeronautics and Space Administration, Houston, 1989, 97 pp.
- [4] D.A. Crawford, P.H. Schultz, The production and evolution of impact-generated magnetic fields, *Int. J. Impact. Eng.* 14(1993) 205-216.
- [5] J.H. Allton, *Catalog of Apollo Lunar Surface Geological Sampling Tools and Containers*, National Aeronautics and Space Administration, Houston, 1989, 97 pp.

11. Investigation: Evaluate the effect of impacts on the evolution of the Martian crust.

Impact is arguably the most important of the processes shaping the crust and surface of Mars. A firm understanding of effects of impacts on the structural, topographic and thermal history is a prerequisite for any broad understanding of the Martian crust and surface. Understanding impact effects requires geologic mapping using global topographic data combined with high-resolution images and remote sensing.

Remote sensing observations of the Martian surface have revealed the dominant role played by impacts in the geologic evolution of the planet. Although other geologic processes contribute, impact cratering with its associated ejecta blanketing and target fracturing is a dominant contributor to regolith formation. Sample return from both the original bedrock as well as from craters exhibiting a range in apparent formation ages would provide constraints on the crater production rate (see III.A.3) that in turn would provide insights into the rate of regolith production. A regolith sample would be important to understanding how quickly the regolith is overturned by other processes. On the Moon, impacts of micrometeorites churn the regolith and provide a mechanism for its overturn (“impact gardening”). A similar regolith sample, preferably a core that extends 2 to 3 centimeters into the regolith, could provide insights into the relative roles of small impacts, aeolian, and other geologic processes in overturning the Martian regolith. Compositional analysis of such a sample would be important to understanding how well the regolith can trap volatiles near the surface for extended periods of time.

Analysis of a sample retrieved from a layered ejecta blanket could be used to test the hypothesis that subsurface volatiles are primarily responsible for formation of this ejecta morphology. Theoretical considerations suggest that impacts into volatile-rich crust produce more impact melt than impacts into drier materials. Investigations at Haughton Crater on Devon Island, Canada, provide observational support for this idea. The proportion of impact melt in a small sample from a Martian layered ejecta blanket could be compared with impact melt from lunar samples to determine if there is support for this hypothesis.

Impact crater formation deposits a substantial amount of heat into the crust adjacent to the crater. If the crust is volatile-rich, this can create hydrothermal systems (see III.A.8). The temporal extent of such systems depends on the size of the crater, amount of volatiles in the crust, and external climate conditions. Long-lived impact-induced hydrothermal systems have been proposed for craters larger than ~25-km-diameter during early Mars history based on numerical modeling, but the lifetime of hydrothermal systems associated with recent large

impacts is unconstrained. Retrieval of samples from the crater rim or central peak/pit could be analyzed for the presence of hydrothermal minerals. Retrieval of such samples from several craters of various sizes and ages could be used in numerical models to better constrain the conditions under which impact-induced hydrothermal systems form.

Sample types needed. A core sample of the regolith that extends 2-3 cm would be desired. Other core samples or chips of impact target rock as well as impact ejecta/melt would be required.

Sample diversity needed. Samples representing a range of locations within a crater as well as from craters of various sizes and ages would be desired.

Physical condition (rock, pulverized rock, etc.). The core sample of regolith ideally would maintain its original layering and some indication of its original orientation relative to the surface.

Contamination types and limits that affect this investigation. None specified.

Sample number and mass. A regolith core would be the minimum requirement. Sample sizes of 300 mg to 1 g should be sufficient for this investigation.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Not specified.

Maximum sample temperatures for sample integrity. Not specified.

Impact of degradation on the investigation. Not specified.

Required/preferred sampling hardware. A rock corer and sample container that could be sealed to prevent loss of any volatiles contained within it.

Data needed for sample choice and in situ characterization. Not specified.

Estimate of required mobility range. Impact regolith is ubiquitous and could be expected to be accessible with minimal driving (<1 km). Other targets of interest like crater rims or peaks may require a few to 10s of km driving.

B. Objective: Characterize the structure, composition, dynamics, and evolution of Mars' interior (investigations in priority order)

Investigating the internal dynamics and structure of Mars contributes to understanding the bulk chemical composition of Mars, the evolution of its crust and mantle, and the origin of its magnetic field and the nature and origin of the minerals that record the field. These are fundamental aspects of Mars that form the basis of comparative planetology.

1. Investigation: Characterize the structure and dynamics of Mars' interior.

Understanding the structure and dynamical processes of the deep interior is fundamental for understanding the origin and evolution of Mars in general, and its surface evolution and the release of water and atmospheric gasses in particular. For example, the thickness of the crust and the size of the core provide strong constraints on the bulk composition of the planet and the manner in which it differentiated. This investigation requires mineralogic, isotopic, seismic, magnetic, gravity and heat flow data bearing directly and indirectly on interior structure and processes.

The most profound advances in understanding the interior structure and dynamics of the Earth have been derived from seismology, supplemented by measurements of heat flow, magnetism, gravity, and electromagnetics. Without a Mars geophysical network, essential progress on this investigation would be limited. Nonetheless, the petrologic, mineralogic, elemental, and isotopic signatures recorded in returned Mars samples could provide useful information on how thermal and differentiation history affected planetary structure and dynamics

Basaltic lithologies from known locations would provide insights into the rate of basalt produced from the Martian mantle when combined with orbital spectroscopy and age dating. Further, basalts would provide insights into the array of potential mantle reservoirs, mantle redox state, estimates of the bulk composition of the Martian mantle and initial estimates of the size of the Martian core. Distinctly different measurements such as magnetic properties of basalts combined with crystallization ages and siderophile element abundances may yield a wide range of information about the composition and dynamics of the Martian core. Experimental studies of basalts that approach liquid compositions would yield information concerning the minimum depth of mantle melting. The basalt lithologies may also yield information on the volatile content of Martian basaltic magmas that have profound implications for mantle degassing and the role of volatiles in a variety of mantle processes (i.e. magma transport, early differentiation). Finally, laboratory measurements of density and seismic velocity of returned samples could help constrain deep petrology inferred from future geophysical measurements at Mars.

With the need for basaltic rocks to be used in compositional, magnetic, and geochronologic studies, the samples for this investigation overlap with those of IIIA3,4,6,10; B2,3.

Sample types needed. Basaltic lithologies from known locations. The optimum samples for geochronology would be unshocked igneous rocks from the beginning of the Hesperian epoch, in order to provide an absolute age for this major transition in Martian geology.

Sample diversity needed. The collection of a series of deep crustal lithologies would allow the reconstruction of crustal structure, crustal temperatures, and history of crustal extraction from the Martian mantle. A wide range of possible deep crustal lithologies may be accessible. They may include igneous complexes, metamorphic terrains, and hydrothermal systems. Such samples could be used to determine whether there are relationships between crustal structures as indicated by these lithologies and orbital geophysical observations

Physical condition (rock, pulverized rock, etc.). Intact cores or whole rocks known to be derived from bedrock would be the best samples, but chips would be acceptable. Powders would not provide textural and mineralogical context for other sets of geochemical data. Further, powders would be contaminated far too easily. Samples should have limited degrees of shock and alteration.

Contamination types and limits that affect this investigation. It would be somewhat detrimental to have the basalts interacting with volatiles derived from volatile-bearing phases (sulfates, clays) in the same sample containment vessel.

Sample number and mass. The number would be site dependent. Total mass that would be required for analytic studies is 0.1-1g per lithology; petrophysical measurements could drive this requirement higher.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Basaltic samples for this investigation would be relatively insensitive to degradation. There would be no stringent storage requirements.

Maximum sample temperatures for sample integrity. Not specified.

Impact of degradation on the investigation. Not specified.

Required/preferred sampling hardware. Coring would be desirable but not required.

Data needed for sample choice and in situ characterization. The ability to identify and distinguish among various basaltic lithologies would be needed.

Estimate of required mobility range. This would be entirely site dependent. For example, at the Meridiani Planum site no basalts have been observed that are locally derived, unlike at the Gusev crater site, where locally derived basalts are ubiquitous. However, several kilometers of driving was required to encounter basalts of different composition.

2. Investigation: Determine the origin and history of the magnetic field.

Evidence that Mars had a magnetic field early in its history has important implications for its formation and early evolution, as well as for the retention of its early atmosphere and for the shielding of the surface from incoming radiation and the possible evolution of life. Requires high-precision, high-resolution global, regional, and local magnetic measurements, as well as mineralogic, isotopic, seismic, gravity and heat flow data bearing on interior structure and processes.

See III.A.10.

3. Investigation: Determine the chemical and thermal evolution of the planet.

Knowledge of the chemical and thermal evolution places constraints on the composition, quantity, and rate of release of volatiles (water and atmospheric gasses) to the surface. This investigation requires measurements of the internal structure, thermal state, surface composition and mineralogy, and geologic relationships.

There are numerous contributions to the investigation of Mars' chemical and thermal evolution that could be made by a Mars sample return. The return of basaltic lithologies from known locations would provide insights into the rate of basalt produced through the melting of the Martian mantle. Placing these data within the context of orbital observations would more firmly establish this rate on a planetary scale. Further, basalts would provide insights into the array of potential mantle compositions, estimates of the bulk composition of the Martian mantle, initial estimates of the size of the Martian core, and the chemical-thermal regimes during initial planetary differentiation. Experimental studies of true liquid compositions would yield information concerning depth of melting.

The collection of a series of deep crustal lithologies would allow the reconstruction of magmatic and thermal evolution of the early Martian crust. This would include finding and sampling both metamorphic rocks, rocks that represent igneous complexes emplaced into these types of deep crustal environments, and crustal remnants of initial Martian differentiation.

Sampling fossil hydrothermal systems would provide evidence for heat and fluid transfer through the Martian crust, the thermal and compositional history of these systems, and allow the identification of different types of crust, mantle, and atmospheric components contributing to these systems. Radiogenic and stable isotopic measurements of phases deposited in these systems would provide age, temperature, redox conditions and fluid composition. Stable isotopic compositions may also yield fingerprints of biologic activity. Fluid inclusions in mineral phases would also provide insights into evolving fluid composition and temperature.

Finding and sampling differentiated magmatic rocks (andesites, silicic rocks such as rhyolites and granites) in the Martian crust would yield important information concerning growth of the crust and lithosphere. If such rocks exist, their magmatic petrogenesis and relationship to tectonic processes on Mars could be investigated.

Samples acquired for this investigation would serve other Goal III investigations including A3,4,6,10 and B1 and B2. Sample requirements essentially are identical to those of B1.

Sample types needed. Basaltic lithologies from known locations.

Sample diversity needed. The collection of a series of deep crustal lithologies would allow the reconstruction of crustal structure, crustal temperatures, and history of crustal extraction from the Martian mantle. A wide range of possible deep crustal lithologies may be accessible. They may include igneous complexes, metamorphic terrains, and hydrothermal systems. Such samples could be used to determine whether there are relationships between crustal structures as indicated by these lithologies and orbital geophysical observations

Physical condition (rock, pulverized rock, etc.). Intact cores or whole rocks known to be derived from bedrock would be the best samples, but chips would be acceptable. Powders would not provide textural and mineralogical context for other sets of geochemical data. Further, powders would be contaminated far too easily. Samples should have limited degrees of shock and alteration.

Contamination types and limits that affect this investigation. It would be somewhat detrimental to have the basalts interacting with volatiles derived from volatile-bearing phases (sulfates, clays) in the same sample containment vessel.

Sample number and mass. The number would be site dependent. The total mass that would be required for analytic studies is 0.1-1g per lithology; petrophysical measurements could drive this requirement higher.

Vulnerability of samples to degradation effects (T, volatile loss, etc.). Basaltic samples for this investigation are relatively insensitive to degradation. There would be no stringent storage requirements.

Maximum sample temperatures for sample integrity. Not specified.

Impact of degradation on the investigation. Not specified.

Required/preferred sampling hardware. Coring is desirable but would not be required.

Data needed for sample choice and in situ characterization. The ability to identify and distinguish among various basaltic lithologies would be needed.

Estimate of required mobility range. This would be entirely site dependent. For example, at the Meridiani Planum site no basalts have been observed that are locally derived, unlike at the

Gusev crater site, where locally derived basalts are ubiquitous. However, several kilometers of driving was required to encounter basalts of different composition.

4. Investigation: Study the structure, dynamics and composition of Phobos and Deimos as indicators of the formation and early evolution of Mars.

Dynamical arguments suggest that the origin of Phobos and Deimos are intimately connected with that of Mars itself. The dynamics of their orbits may provide constraints on the structure of Mars' interior and their composition may provide further clues to its evolution. This investigation is not aimed at detailed studies of Phobos and Deimos, but rather at using their properties to constrain the composition and evolution of Mars.

No perceived relevance to sample return (from Mars proper).

GOAL IV

Introduction and Synthesis

Martian robotic missions could serve an essential function as precursors to the eventual human exploration of Mars. This is analogous to the role Ranger, Surveyor and Lunar Orbiters played in paving the way for Apollo and that the Lunar Reconnaissance Orbiter would do for the next phase of human lunar exploration. Recognizing that potential, MEPAG included Goal IV - Prepare for Eventual Human Exploration - to its Mars Science Goals, Objectives, Investigations, and Priorities document. Goal IV addresses science and engineering questions specific to increasing the safety, decreasing the cost, and increasing the productivity of human crews on Mars. Goal IV describes both the data sets that are to be collected and analyzed (Objective A), and the demonstrations of critical technologies that must be validated in the actual Martian environment (Objective B). Although robotic science missions have science as their prime goal, it is prudent and sensible to examine them to see how they might contribute to Goal IV. In that regard, we herein look specifically at how Mars sample return missions could help accomplish Goal IV objectives.

Each investigation of the Goal IV Objectives was examined to see what requirements might be imposed on the acquisition of martian samples in order to satisfy the investigation. A general conclusion is that a Mars sample return could contribute uniquely to many of the Goal IV investigations with priorities ranging from high to low. For example, gaining a comprehensive understanding of the toxicity, electrostatic and biohazard potential of martian particulates, whether airborne dust or regolith, is high priority in that it could best be determined by analyzing returned sample. At the other end of the spectrum, at low priority, determining the engineering properties of martian regolith for trafficability purposes and developing simulants benefits markedly from laboratory analysis of soil particles (chemical and mineralogical composition, shape, size distribution, hardness, etc.) but would demand dedicated in-situ soil mechanics measurements, at sites where humans would actually land, to provide the bulk of needed data. The same holds for investigating the potential for using martian water (bound or otherwise) as an ISRU feedstock. At the extreme, sample return would do relatively little for understanding atmospheric and meteorological properties pertaining to EDL and surface operations.

Fortuitously, the high priority Goal IV requirements could be largely satisfied with samples collected primarily for science investigations; e.g., Goal IV dust and regolith sample needs would be redundant to first order with science needs regarding diversity, context, acquisition and packaging; it is important, however, to consider that engineering measurements may require slightly more sample mass. Some Goal IV investigations could lead to special sample acquisition or handling such as the desire to obtain sample downwind from the lander to aid in determining the potential for forward planetary contamination. A special opportunity has been identified for studies of materials degradation that envisions the application of coupons of different materials to some of the sample return containers. This would apply mostly to Mars sample return scenarios that utilize a dedicated sample caching mission that would be on Mars for several years prior to sample return.

There are two aspects of Mars sample return missions that would not be investigation dependent yet could contribute materially to human exploration aspirations. First is the “fact of” demonstration of the ability to conduct a round-trip mission to Mars. Mars sample return would demonstrate for the first time the ascent of a vehicle off the surface of Mars and the subsequent

entry at Earth. Second, the greatly improved science understanding of Mars would inevitably provide a sounder, more productive basis for designing the scientific research to be conducted by human missions. Proof-of-concept for this feed-forward is 30 years old, coming from studying how analyses of the returned samples from early Apollo missions significantly enhanced the science accomplished on later missions.

In summary, Mars sample return missions would have a significant low-cost contribution to make to preparing for human exploration of Mars. NASA's human exploration and science communities should work closely together to gain the reality of the potential.

Objective A. Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.²

Investigations #1A-1D are judged to be of indistinguishable high priority.

Investigation 1A. Characterize the particulates that could be transported to hardware and infrastructure through the air (including both natural Aeolian dust and other materials that could be raised from the martian regolith by ground operations), and that could affect engineering performance and in situ lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

Measurements

- a. A complete analysis, consisting of shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations.

Note #1: For sites where air-borne dust naturally settles, a bulk regolith sample is sufficient—analysis of a separate sample of dust filtered from the atmosphere is desirable, but not required.

Note #2: Obtaining a broad range of measurements on the same sample is considerably more valuable than a few measurements on each of several samples (this naturally lends itself to sample return).

Note #3: There is not consensus on adding magnetic properties to the list of measurements.

- b. Characterize at least one regolith deposit with fidelity sufficient to establish credible engineering simulation labs and/or software codes on Earth to solve engineering problems related to differential settlement of the regolith, and plume/regolith interactions (see Note #4).

² General Notes:

- *Except as noted, investigations are listed in priority order. Within each investigation, measurements are listed in priority order.*
- Prioritization Criteria:
 - *Magnitude of effect of precursor information on reduction of risk and/or cost of a human mission to Mars.*
 - *Perceived degree of viability and cost of available mitigation options.*
 - *Potential to obtain minimum necessary information in a less expensive way than by flying a mission to Mars.*

1. For one site on Mars (see Note #5), measure the following properties of the regolith as a function of depth to 1 meter:
 - (i) Particle shape and size distribution
 - (ii) Ice content and composition to within 5% by mass
 - (iii) Regolith density to within 0.1 g/cm³
 - (iv) Gas permeability in the range 1 to 300 Darcy with a factor of three accuracy.
 - (v) Presence of significant heterogeneities or subsurface features of layering
 - (vi) An index of shear strength
 - (vii) Flow Rate Index test or other standard flow index measurement
2. Repeat the above measurements at a second site in different geologic terrain:
- c. The same measurements as in a) on a sample of air-borne dust collected during a major dust storm.
- d. Subsets of the complete analysis described in a), and measured at different locations on Mars (see Note #2). For individual measurements, priorities are:
 - i. shape and size distribution and mineralogy
 - ii. electrical
 - iii. Chemistry

Note #4. Because there is a large engineering lead-time required to solve the geotechnical problems, these data must be obtained early in the precursor program.

Note #5. These measurements should be made in a competent regolith deposit as opposed to loose drift material (cohesionless sand dunes), as landing is expected to attempt to avoid the looser material. Also, if mission planners were to select high latitude polar deposits for a human landing site, geotechnical data would be required from a representative location of those deposits. These measurements should include polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities. Measurement should be taken during the day in calm conditions representative of nominal Extra Vehicular Activity (EVA) excursions.

Investigation IVA-1: Implications for sample return.

Analysis Leader: Phil Metzger, Paul Carpenter, and Brad Joliff.

Two sub-topics are comprehended in this investigation, and they shall be addressed in this order: (1) bulk mechanical properties of the soil component of the regolith plus its ice content, and (2) physical and chemical properties of the regolith particles including soil and dust fractions.

Bulk Mechanical Properties

(1) It is hard to justify sample return on the basis of soil mechanics. The general consensus among soil mechanics experts is that *in situ* measurements are more valuable than sample return for understanding the bulk mechanical properties of the soil. That is because soil mechanics is highly dependent upon the environment and the undisturbed properties of the soil, such as the compaction, fabric, and stress pre-loading of the soil before it is excavated. As a result, the first priority for soil mechanics would be to make high-fidelity measurements *in situ* at a suitable number of locations, and there are divergent opinions among soil mechanics experts whether a sample return for the purposes of soil mechanics is justifiable or necessary. This is consistent with knowledge gained about bulk mechanical properties of lunar soil from Apollo surface EVA experience.

Nevertheless, certain aspects of the soil mechanics could not be fully understood unless measurements are made in a laboratory environment. These would include measurements of the soil's dilatancy, strength, and stiffness, which are ordinarily measured with a suite of specialized laboratory instruments. If samples are not returned from Mars, then the soil mechanics modeling would not achieve the highest fidelity prior to the arrival of humans unless special instruments are developed to enable making these measurements *in situ*. Significant technology advances would be required to make these instruments lightweight, accurate, and reliably autonomous for implementation on a spacecraft, and it is likely that a practical set of spacecraft instrumentation would still leave questions unanswered about the mechanical behavior of the soil. Therefore, at least some soil mechanics experts believe that it would be prudent to return sufficient soil from one or two representative sites in order to develop a higher fidelity basis for soil mechanics models. But this is not a conclusion of the consensus. Certainly something like 90% of the needed knowledge of the soil mechanics could be obtained using a reasonable set of instruments on a robotic spacecraft, and this probably would be sufficient to achieve program objectives.

Another argument that limits the value of sample return for soil mechanics is that different soil deposits have vastly different mechanical properties, and so returning one or two samples would not provide sufficient data for most of the places that may be visited in the exploration program, anyway.

The particular measurements described in the 2006 MEPAG Goals document, Goal IV, Objective A, Investigation 1a, were designed to be able to perform them *in situ*, and hence by definition no sample return would be required to measure these parameters. However, in some cases, sample return would provide some benefit. These are:

(i) Particle shape and size distribution

Could be measured by microscopy using a vibrational or compressed-gas particle delivery method (to effect particle separation) to the microscope

(ii) Ice content and composition to within 5% by mass

Volatiles could be measured by gravimetrics and by mass spectrometry as they are thermally driven from a sample. However, sample return would provide for a more complete chemical assay of the ice content

(iii) Regolith density to within 0.1 g/cm³

Could only be measured *in situ*. All returned samples should have the relative density measured or estimated (by volume measurement, e.g., photographic analysis of the removal site) prior to return to aid the subsequent analysis.

(iv) Gas permeability in the range 1 to 300 Darcy with a factor of three accuracy.

Would be best measured *in situ* since extraction changes the porosity of the sample. However, samples that are epoxy-stabilized prior to return would also support estimation of the gas permeability through computer analysis of thin sections.

(v) Presence of significant heterogeneities or subsurface features of layering

Could be assessed only *in situ*.

(vi) An index of shear strength

It is generally agreed that the index tests are difficult to extrapolate or interpret apart from an existing base of experience, which does not yet exist for Martian soil. Yet, a measurement of this sort is so basic that it must be done. Also, index tests would be the easiest for an astronaut to perform, or for a rover spacecraft to perform robotically on multiple sites, and so a more careful set of index measurements should be performed with higher-fidelity instruments first in order to provide the beginnings of the base of experience. This would be best measured in a terrestrial laboratory since the higher-fidelity index testers would be difficult to adapt and operate on Mars without significant uncertainty as to the meaning of the measurements. However, an *in situ* test on undisturbed soil with a vane shear tester at the point of sample extraction would supplement the laboratory measurement, providing a comparison between undisturbed soil and the more careful laboratory measurements on the same sample.

(vii) Flow Rate Index test or other standard flow index measurement

These could be performed *in situ*, but the discussion is very similar to the item above for index tests of shear strength. Laboratory tests in combination with *in situ* tests would be ideal. However, there is no consensus for either case whether or not the sample return would be justified or necessary for these purposes.

Physical and chemical properties of the regolith

(2) Detailed knowledge of the physical and chemical properties of martian dust and soil particles are needed to fully understand health risks to astronauts, behavior of mechanical processes in the martian dust and regolith environment, and processing methods and approaches to development of martian regolith-based resources. Martian regolith, like lunar regolith, represents a mixture of materials that have different sources. Broad compositional variations across the surface of Mars exist, but differ in detail from the compositional variations seen across, for example, the Moon, and the processes leading to compositional variations also differ. Despite such variations, however, much could and would be learned about physical and chemical properties by the first return of martian regolith from a single location. They would indicate surface processes that can be extrapolated to other regions of Mars of differing bedrock and regolith compositional characteristics. For comparison, the first return of regolith from the Moon revealed the presence of glassy agglutinates or fused-soil aggregates formed by solar wind implantation and micrometeorite bombardment. Although agglutinates are not expected to form in martian regolith because of the presence of an atmosphere, other unanticipated but important particles may be found.

The makeup and characteristics of the grains that constitute dust and regolith are difficult to study *in-situ* because of very fine grain sizes of the chemical and mineral constituents. MER results show the fine soil to be composed of composite or multimineralic grains with constituent or sub-grain sizes of less than 30 μm and the characteristics of the dust suggest that much of it probably exists in the sub-micron size range. Martian dust is very well mixed and homogeneous

on a global scale because of frequent and giant regional dust storms that, at times, coalesce into global dust clouds. To the extent that it has been studied in-situ and sensed remotely, the martian regolith is more variable than martian dust. For the most part, it is basaltic to andesitic in composition, but with a strong sulfate component, generally 5-7 wt.% S as SO₃. Locally, soils can be quite variable, such as in parts of Gusev crater explored by Spirit where silica and sulfate concentrations are locally very high. As coarser regolith grains are considered, they reflect more and more the character of local bedrock, and the bedrock has been shown by surface exploration to be quite variable, although strongly basaltic in many places.

Despite the significant knowledge gained about dust and regolith materials by surface exploration, especially that of the MERs, much remains unknown about the physical properties and details of mineralogy and chemistry of the grains that make up martian regolith.

Physical properties of grains include grain size and size distribution, shape, hardness, fracture and strain, crystallinity, compaction and cohesion characteristics, magnetic susceptibility, mineral assemblage, and chemical reactivity in different environments that may cause mineralogical or other physical phase changes.

Chemistry and mineralogy properties include bulk chemistry, mineral speciation, mineral chemistry, oxidation state, and volatile contents, especially OH and H₂O. Chemical reactivity and variations as a function of exposure to martian or terrestrial (in the case of sample return) environments is not yet well known.

Investigation Summary: Sample needs/priorities

Priority for first sample return: HIGH

Sample types required:

1. Dust sample. Because martian dust is globally homogeneous, the first sample would be extremely important. Much has been learned about the magnetic properties and mineralogy of martian dust through the MER mission; however, the dust needs to be understood on the size scale of individual mineral and grain constituents. As mentioned above, these are extremely fine-grained, extending into the sub-micrometer range. To fully understand processes that generate the dust and its full range of physical properties including those related to reactivity and potential health concerns, dust particulates and adhering or adsorbed components must be studied by high-magnification methods such as scanning electron microscopy, transmission-electron microscopy, electron-probe microanalysis, secondary-ion mass spectrometry, laser-desorption mass-spectroscopy, and others.
2. Regolith sample(s) beneath surficial dust deposits. The dust layer as experienced by landed missions on Mars is generally very thin. Beneath dust coatings is regolith that may consist of wind-blown sediments and admixed materials from weathering of underlying or nearby bedrock and materials excavated by nearby impact craters. Aeolian processes can very effectively sort materials locally, thus care must be taken to obtain multiple samples that would provide a representation of the local variability and not a single well-sorted grain type or size. In general, regolith samples derived from missions subsequent to the first sample return that represent significantly different source or local geology would be highly valuable, especially with respect to characteristics such as volatile content, mineralogy, and considerations related to resource potential.

Simulants

We have a significant body of knowledge based on studies of lunar samples that motivates the development of lunar regolith simulant materials. A minimum set of simulants for lunar technology development is a basaltic mare simulant, a gabbroic anorthosite highland simulant, and additive materials such as ilmenite, glass, and specific components like nanophase iron. These simulants are being developed sequentially according to budget restrictions and priorities. To date, the approach has been to make use of material that is readily available with only milling and sieving in order to produce the necessary lunar grain size distribution. Lunar mare simulant JSC-1 and JSC-1A are obtained from basaltic ash from the Meriam crater in Arizona, and a lunar highland simulant is under development using gabbroic and anorthositic materials obtained from the Stillwater intrusion in Montana. These materials are milled, homogenized, and then sieved with no other processing. High fidelity simulants can be produced by mixing mineral, glass, and rock fractions obtained from multiple sources, but this will be a complex and costly approach which will only make sense for reduced quantities of material. One can anticipate planning for hundred ton quantities of final simulant for physical purposes, and tens of tons for chemical processes. Experience with usage demands to date indicates a desire to work with simulant very early in technology development when perhaps simplified materials should be used, and also that users desire to consume large quantities of simulant before developing efficient usage schedules for material. Distribution of simulant to NASA centers has been in quantities no smaller than 1 ton lots. An understanding of the lunar simulant program and the perspective gained from that experience should be applied to discussions concerning the development of martian simulants.

For all discussions of simulant development, it is important to discern between processes and activities that are primarily physical as compared to those that are chemical in scope. Simulants that have high fidelity in matching the planetary regolith become more important as the process transitions from physical to chemical. For example, it is likely that excavation and drilling depend more on physical simulant properties, and oxygen extraction depends more on chemical and mineralogical properties. The analysis of process and activities leads to a prioritization of material properties of candidate simulant materials for further development.

The martian regolith has not been characterized as intensively in comparison to the lunar regolith. However, martian materials are predominantly basaltic in composition, with a significant proportion of wind-blown dust. Compositional analysis by the MER rovers indicates the presence of sulfate as SO_3 and chloride in addition to compositions that are nominally basaltic. From our knowledge of the martian soils the likely set simulant materials should include:

1. Martian basaltic regolith simulant. This simulant should have a grain size distribution of a typical martian soil, with a size cutoff at both coarse and fine grain sizes that are appropriately chosen. The material properties of the simulant should be present in the source material to the greatest extent possible, with only milling and sieving required for use as a simulant. The simulant should be either an average composition requiring no addition of components, or alternatively, a root composition which could be used as a compositional end-member and modified by addition of components to bring it in line with specific martian regolith compositions. This simulant would be comparable to lunar mare basalt simulant JSC-1A.

2. Martian dust simulant. This simulant should be a dust-sized simulant that duplicates the average martian dust, and has a grain size distribution that terminates at a coarse size of, for example, 20 microns. This simulant would be comparable to lunar mare basalt simulant JSC-1AF which is the dust size fraction of JSC-1A and is compositionally equivalent.

There is clearly no substitute for a sample return with respect to complete characterization of mineralogy, texture, and chemistry. On Mars, it is possible that dust and fine soil samples are globally homogenized, so that a relatively few sample locations would be expected to return similar material properties. However, it is likely that significant variations in rock mineralogy and chemistry exist, and have not yet been mapped or otherwise identified by remote sensing, so that more sampling localities would be required in order to document the variation.

The need for sample return would be primarily for analysis of mineralogy, texture, and chemistry, both as precious scientific samples of a planetary body, but also for engineering studies in support of exploration. The necessarily small sample size dictated by a sample return mission could not reasonably be seen as directly supporting geotechnical measurements such as load bearing capacity. However, the properties of samples could be used to model these parameters by scaling up in size. Many geotechnical measurements result in consumption or modification of materials and are therefore unsuited to preserving the nature of a returned sample.

Investigation 1B. Determine the atmospheric fluid variations from ground to >90 km that affect EDL and TAO including both ambient conditions and dust storms.

Measurements:

- a. Measure v , P , T and ρ in the upper, middle and lower atmosphere during EDL. Obtain as many profiles at various times and locations as possible (requested for ALL landed missions). Sample rate should be high enough (~ 100 Hz) to quantify turbulent layers. Specific direct or derived measurements include:
 - Density from 120 km to surface ranging from high altitude values of 10^{-9} to near-surface values of 10^{-1} kg/m³, $d\rho = 1\%$ of local ambient, rate= 100 Hz
 - Pressure from 120 km to surface ranging from high altitude values of 10^{-7} to near-surface values of 15 mb, $dP = 1\%$ of local ambient, rate=100 Hz
 - Temperature 60-300 K, $dT = 0.5K$, rate= 100 Hz (direct measurement may be slower)
 - Directional Wind Velocity, 1-50 m/sec, $dv = 1$ m/s, rate= 100 HzParticular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure is large.
- b. Monitor surface/near-surface $v(z)$, P , $T(z)$, and ρ as a function of time. Quantify the nature of the surface heating driver and associated boundary layer turbulence at altitudes above station. Data defines the initial conditions for high altitude modeling. Obtain data from as many locations as possible (requested for all landed missions). Surface/near surface packages should measure directly: Pressure, at surface, 0.005 mb to 15 mb, $dP = 2$ microb, full diurnal sampling, rate= >10 Hz

- Velocity, at surface, 0.05-50 m/sec, $dv = 0.05$ m/s, horizontal and vertical, full diurnal sampling, rate= 10 Hz
 - Air temperature, at surface, 150-300 K, $dt = 0.04$ K, full diurnal sampling, rate= 10 Hz
 - Ground temperature 150-300 K, $dt = 1$ K, full diurnal sampling, rate= 1 Hz
 - Air temperature profile, 0-5km, <1km resolution, 150-300K, $dt=2$ K, full diurnal sampling, rate=1 Hz
 - Velocity profile, 0-5km, <1km resolution, 1-50 m/sec, $dv=1$ ms/, horizontal and vertical, full diurnal sampling, rate=1 Hz
 - o Opacity, visible, depth 0.2-10, $d\tau = 0.1$, once every 10 min
- c. Make long-term ($\gg 1$ martian year) remote sensing observations of the weather (atmospheric state and variations) from orbit, including a direct or derived measurement of:
- Aeolian, cloud, and fog event frequency, size, distribution as a function of time, over multi-year baseline.
 - Vertical temperature profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times [*Development work required for T from surface to 20 km*].
 - Vertical density/pressure profiles from 0-120 km with better than 1 km resolution between 0-20 km, 1-3 km resolution between 20-60 km, 3 km resolution > 60 km and with global coverage over the course of a sol, all local times [*Development work required for ρ from surface to 20 km*].
 - 3-D winds as a function of altitude, from 0-60 km with better than 1 km resolution below 20 km, and 1-3 km resolution between 20-60 km, and with global coverage over the course of a sol, all local times [*Development work required at all altitudes for an independent means to derive V, with special emphasis from surface to 20 km*]. Note particular emphasis on measurements between 0-20 km to quantify boundary layer wind and turbulence and 30-60 km where vehicle dynamic pressure would be large. At time of human EDL and TAO, deploy ascent/descent probes into atmosphere to measure P, V, and T just prior to human descent at scales listed in 1Ba.

Note #6: We have not reached agreement on the minimum number of atmospheric measurements described above, but it would be prudent to instrument all Mars atmospheric flight missions to extract required vehicle design and environment information. Our current understanding of the atmosphere comes primarily from orbital measurements, a small number of surface meteorology stations and a few entry profiles. Each landed mission to Mars has the potential to gather data that would significantly improve our models of the martian atmosphere and its variability. It is thus desired that each opportunity be used to its fullest potential to gather atmospheric data. Reconstructing atmospheric dynamics from tracking data is useful but insufficient. Properly instrumenting entry vehicles would be required.

Investigation IVA-2: Implications for sample return.

Analysis Leader: Vicky Hipkin.

Investigations IVA-2, IVA-6 and IVA-10 describe **transient atmospheric phenomena** and hence could not be addressed directly by sample return. Current MEPAG recommendations **do**

not include sample return to address these specific risks. Highest priority for all three investigations are in situ studies (**every** landed Mars mission to carry a surface meteorology package given importance of risk reduction, and at least one landed mission to carry surface electricity package), coupled with multi-year orbital survey to capture statistics on transient events on a global scale. However the understanding of these transient phenomena, especially on the small spatial scales of dust devils, arcing and electrical discharge, depends on the continued refinement of atmospheric models, and could benefit from laboratory studies.

A sample of Mars atmospheric dust could support the validation of these models and provide parameters needed to produce improved Mars dust stimulant for laboratory studies of electrical processes.

A sample of Mars dust acquired from the atmosphere using a filter could be thought to be representative of global Mars dust in terms of **shape and composition** due to the well-mixed state of the Mars atmosphere after a global dust storm (cite).

For GCM's, dust is parameterized for radiative transfer usually by assuming composition (optical properties), a simple single or bimodal size distribution, and shape represented by single scattering albedo and asymmetry factor (e.g., Basu et al., 2006).

For electrical properties studies, differences in particle composition (conductivity) and shape are important parameters that influence the distribution and type of charge. Mars soil simulant JSC-Mars-1 in laboratory triboelectric experiments shows a broad charge distribution which may be related to particle heterogeneity (Sickafoose et al, 2001).

Knowledge of particle composition and shape can be improved from sample return.

Particle size distribution is a useful parameter for both electric and meteorology studies and is influenced by current atmospheric state. A particle size distribution would be measured in a sample collected on a filter. For ease of interpretability thought should go into the atmospheric conditions under which this sample would be collected. Wind speed influences saltation (dust lifting); temperature/radiation influence buoyancy; together these would result in a time dependent particle size distribution with height. Electrical effects may produce a mass-dependent levitation of dust grains from an induced electric field once dust is moving.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

1. dust sample

Priority of samples from a second landing site: LOW

1C. Determine if each martian site to be visited by humans is free, to within acceptable risk standards, of biohazards that may have adverse effects on humans and other terrestrial species. Sampling into the subsurface for this investigation must extend to the

maximum depth to which the human mission may come into contact with uncontained martian material.

Measurements:

- a. Determine if extant life is widely present in the martian near-surface regolith, and if the airborne dust is a vector for its transport. If life is present, assess whether it is a biohazard. For both assessments, the required measurements are the tests described in the Draft Test Protocol.

Note #7: To achieve the necessary confidence, this would require sample return and analyses in terrestrial laboratories.

Note #8: The samples could be collected from any site on Mars that is subjected to wind-blown dust.

Note #9: At any site where dust from the atmosphere is deposited on the surface, a regolith sample collected from the upper surface would be sufficient--it is not necessary to filter dust from the atmosphere.

- b. At the site of the planned first human landing, conduct biologic assays using in-situ methods, with measurements and instruments designed using the results of all prior investigations. All of the geological materials with which the humans and/or the flight elements that will be returning to Earth come into contact need to be sampled and analyzed.

Note #10: It is recommended that a decision on whether human landing sites after the first one require a lander with biological screening abilities be deferred until after Measurement a) has been completed.

Investigation IVA-3: (Biohazards) Implications for Sample Return.

Analysis Leader: Carl Allen.

The Mars Exploration Program Analysis Group (MEPAG) defined four overall Goals that continue to guide future mission planning. Goal IV is to “Prepare for Human Exploration.” The MEPAG-chartered Human Precursor Science Steering Group recently assessed the implementation of this Goal, and specifically Objective IV-A “Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.” (Beatty et al., 2005). This study recommended four high-priority investigations, including “Determine if each martian site to be visited by humans is free, to within acceptable risk standards, of replicating biohazards which may have adverse effects on humans and other terrestrial species.”

This question can be addressed at two levels – global and human landing site-specific. The global question is particularly appropriate for a first sample return mission. The investigation proposed for this question by the Science Steering Group is “Determine if extant life is widely present in the martian near-surface regolith, and if the airborne dust is a vector for its transport. If life is present, assess whether it is a biohazard. . . . To achieve the necessary confidence, this requires sample return and analyses in terrestrial laboratories.” (Beatty et al. (2005).

The samples and analyses required for such assessment were carefully addressed by a diverse group of experts in five dedicated workshops organized by the NASA Planetary Protection Officer. The resulting “Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth” (Rummel et al., 2002) describes the currently-accepted “minimum set” of analyses acceptable for this assessment.

The following considerations apply to requirements for biohazard assessment on a first sample return mission.

The minimum sample required for global biohazard analysis would be the airborne dust. This material, carried planet-wide by frequent windstorms, integrates fines from across Mars. The major and minor element compositions and reflectance spectra of dust deposits at five widely-separated landing sites are indistinguishable, indicating a well-mixed airborne component.

The sample could be collected from any site on Mars that is subjected to wind-blown dust. At any site where dust from the atmosphere is deposited on the surface, a regolith sample collected from the upper surface would be sufficient.

The sample for return to Earth for biohazard assessment must be minimally altered by the acts of collection and storage. Biological contamination must be kept below sampling hardware sterilization limits required by Planetary Protection (currently Viking-level sterilization). Organic contamination must be kept below Viking-level detection limits (1 ppb).

A single sample of dust would be sufficient to conduct this investigation. The Draft Test Protocol (Rummel et al., 2002) states that 15 – 25 g would be sufficient to carry out all required biohazard testing. The actual protocols to be used for biohazard testing a decade from now may well be more sensitive than those recommended during the 2002 study, resulting in a somewhat lower sample mass requirement.

The environmental tolerance of martian organisms (if any) is unknown, so the sample should be preserved and transported in an environment as little altered as possible. Specifically, it should be kept at or near ambient pressure in a Mars-like atmosphere and at a temperature within the annual temperature range at the sampling site. The effects of exposure to environmental conditions outside of this range are unknown but could include death of viable organisms, alteration of organism remains, and alteration of chemical biosignatures.

The biohazard sample should be collected using sterilized, precision cleaned sampling hardware. If more than one sample is collected, a separate implement to contact each sample preferred is preferred to prevent cross-contamination. Each sample should be placed in a sterilized, precision cleaned, sealable container.

The biohazard sample must be representative of the planet-wide windblown dust. This material could be identified based on its small particle size, elemental composition, and reflectance spectrum.

The lateral mobility range that would be required for collecting a dust sample from a surface deposit is site-specific. Dust coverage on Mars ranges from total to essentially nil. However, the dust cover can be reliably determined from current orbital data, so the range to suitable dust deposits would be known prior to landing. The sample of surface dust would not require vertical mobility beyond that of an arm-mounted scoop.

The biohazard sample would be one of the key materials to be collected, and would be subjected to detailed analysis at the sub-micron scale. It must therefore be stringently protected from contamination from the sample handling equipment and from cross-contamination by other samples. The biohazard sample must be stored in a dedicated container designed to remain intact and sealed until secured in the Sample Receiving Facility (SRF) on Earth. Additional martian samples must also be maintained in one or more sealed containers until secured in the SRF, but requirements for separate packaging of these samples would be determined by other research criteria.

All material from the first Mars sample return mission must be treated as a high-level biohazard until the actual level of biohazard is determined by analyses on Earth. These analyses must, at a minimum, meet the requirements of the Draft Test Protocol (Rummel et al., 2002) or its updated equivalent.

Investigation Summary: Sample needs/priorities

Priority for first sample return: HIGH

Sample types required:

1. dust sample (scoop acquisition is OK)

Priority of samples from a second landing site: LOW

Investigation 1D. Characterize potential sources of water to support In Situ Resource Utilization (ISRU) for eventual human missions. At this time it is not known where human exploration of Mars may occur. However, if ISRU is determined to be required for reasons of mission affordability and/or safety, then the following measurements for water with respect to ISRU become necessary (these options cannot be prioritized without applying constraints from mission system engineering, ISRU process engineering, and geological potential):

Measurement Options:

- a. Perform measurements within the top few meters of the regolith in a location within the near-equatorial region (approximately $\pm 30^\circ$) that the Mars Odyssey mission indicates is a local maximum in hydrogen content, to determine: (i) concentration of water released upon regolith heating, (ii) composition and concentration of other associated volatiles released with water, and (iii) three-dimensional distribution of measurements i & ii within a 100 meter x 100 meter local region. This option would include water contained in hydrous minerals, as adsorbed water, and in any other form it might be present in the regolith. Either unconsolidated or loosely consolidated regolith is a focus of current attention because of the need to minimize mining engineering, but outcrops of rock containing hydrous minerals may also be a valuable possibility if they are sufficiently friable.
- b. Perform measurements to (i) identify and determine the depth, thickness, and concentration of water in subsurface ice deposits to a few meters depth at approximately 40° to 55° latitude, (ii) determine the demarcation profile/latitude where near-surface subsurface ice formation does and does not occur.
- c. Perform measurements in the polar region (70° to 90°) to determine the depth, thickness, and concentration of near-surface water/ice.
- d. Measurements for water at other locations and depths are not precluded but require further scientific measurements and/or analysis to warrant consideration. This option would specifically include accessing a deep aquifer.

Investigation IVA-4: Implications for sample return.

Analysis Leader: Ben Clark.

For In Situ Resources, the most valuable potential constituent would be H₂O, and this could exist in loosely bound, tightly bound, and/or chemically incorporated forms. For minimum energy cost, the loosely bound H₂O would be the most valuable, but also the most difficult to contain during sample acquisition when digging into the regolith. Although it could be captured if the acquisition system works fast, it would require many separately sealed containers to properly characterize the depth distribution of H₂O. Sealing an entire deep core of material as one item would allow subsequent vertical re-distribution during return to Earth. Thus, an in situ experiment probably would be far more appropriate, informative and precise for H₂O determination. An example instrument would be the Thermal Evolved Gas Analyzer (TEGA) on the Phoenix Mars Scout mission.

Tightly bound H₂O may actually survive the return trip, although sealing still might be desired. Chemically incorporated H₂O, such as in clay mineral structures (as hydroxyl) should fully survive return without the necessity of sealed containers and could be analyzed on Earth. Various maximum permissible temperature limits to maintain sample preservation have been proposed for various putative hydrous minerals. However, ISRU would be most particularly interested in the quantitative relationship between energy expenditure and release of H₂O, mapped as a function of quantities versus depth and possible horizontal heterogeneities in the regolith, which could be done more accurately, comprehensively and exhaustively on site at Mars.

Investigation Summary: Sample needs/priorities

Priority for first sample return: MEDIUM

Sample types required:

1. regolith sample (sample must be encapsulated with air-tight seal)

Priority of samples from a second landing site: HIGH if second landing site has different attributes related to water content.

The following investigations are listed in descending priority order.

Investigation 2. Determine the possible toxic effects of martian dust on humans.

Measurements:

- a. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species such as CrVI. (Might require a Mars sample return).
- b. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith from a depth as large as might be affected by human surface operations.
- c. Analyze the shapes of martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).
- d. Determine if martian regolith elicits a toxic response in an animal species that are surrogates for humans.

Investigation IVA-5: (Toxicity) Implications for sample return.

Analysis Leader: Jeff Jones with John James, Russ Kerschman, David McKay, Mark Ott

Context

Potential toxicity of returned martian soil and dust can be conveniently grouped into two categories:

1. Toxicity from chemical and mineralogical properties (CM- Toxicity).
2. Toxicity from biological properties. (B-Toxicity)

While not mutually exclusive, this grouping into two major sub categories helps systemize the issues and approaches.

CM-Toxicity of dust

For lunar dust, only CM- Toxicity is relevant^{1,2}. No biological activity of any kind has been found on the moon and none is expected³; B-Toxicity does not exist in lunar dust³. We have addressed the CM-Toxicity issues for lunar dust (defined as <20 µm soil).

We have evidence from Apollo samples, that short term exposures to lunar regolith are irritating to the mucous membranes and respiratory epithelium in some humans, with varying sensitivity, however, there is no current evidence of permanent sequelae from the Apollo very short duration exposures. It must be considered, that most terrestrial diseases associated with dust exposure (e.g. anthracosis, silicosis, etc., the exception being for freshly fractured quartz) occur after longer duration of contact with the dust.

We are doing toxicologic studies now with lunar simulant and a limited quantity of Apollo dust in rodents and human volunteers. Tests include intratracheal, corneal, dermal and ingestion studies that would allow validation of toxic effects. After the lunar dust toxicological studies are complete (estimated by end of 2008), we will have a much better idea of the minimum amount of martian sample needed for reliable testing. However, at this point, we estimate that 100 grams of actual martian dust will be the maximum requirement, and we can only accurately determine the minimum requirement after our test program, but we currently estimate that 20 grams would be necessary. In parallel with lunar dust simulant testing and Apollo soil dust testing, we would prefer to conduct toxicity testing on appropriate martian dust simulants now available. Results will provide better mass requirements for returned martian soil and dust.

Sample priorities

1) Returned amount should be in the range of 20 to 100 gm (subject to review at the end of testing in 2008). This would enable microbiological activity assessment, chemical and morphological assessment focusing on biological correlates, and mechanical, chemical and biological toxicity assessment. The morphological (surface area, shape, size distribution, adhesion properties) and chemical (compositional and reactivity) studies to allow biological understanding may significantly overlap with geological science analyses, and the data would be shared by both scientific communities. The size of interest for toxicity is in the <20 µm size fraction, esp. <5 µm range.

The most essential tests could be carried out using much smaller samples: a minimal quantity from which meaningful toxicological studies alone, with adequate "n" size, could be conducted with as little as 3 g.

The preference is to obtain multiple small samples of regolith (e.g. five 5-gram samples) than one larger 25-gram sample. Obviously, if there are multiple samples, they would need to be encapsulated. While global dust storms may tend to homogenize dust over the martian surface,

local rock types, chemistry, and present and past processes may add a distinctive character to dust from each collection site, and such heterogeneity should be anticipated.

2) The minimum sample set would be at least two regolith samples. Q: If these are collected 1 km apart, would that be sufficient, or would they need to be separated on a planetary scale? Q: Could you justify more samples than 2, or would two be sufficient?

A: The regolith samples would need to be kept distinct, so as to be able to interpret heterogeneity. The samples could be a km apart if we only needed to assess toxicity of a specific destination; however if we want to determine regolith toxicity planetary wide, then we would need samples from multiple regions. We know the lunar mare regions have regolith with significance compositional differences than the highlands, etc. Data from Spirit and Opportunity show that surface soils can have significantly different variations in albedo and chemistry and that these variations can occur over short distances (<1 meter). Whether these differences would influence potential toxicity studies cannot be predicted in advance. Therefore it would be necessary to return samples of each major distinctive soil type based on albedo, spectral properties, and chemistry. This requirement would likely parallel the requirement of the chemical/mineralogical team, so the same set of samples could be split between this team and the toxicology team.

We would also require a minimum of two depth samples from the deepest part of the martian regolith sampled by the lander/rover. The purpose of these samples would be to assess whether potential toxic properties vary with depth. Such properties may include the surface reactivity of dust grains, the possible presence and abundance of particularly toxic species such as hexavalent chromium, and the variation of oxidation potential, pH, and toxic metals with depth.

3) Samples should be preserved in a vacuum-sealed container; however if a vacuum is not achievable, then the samples should be in a container sealed in Martian atmosphere. We need them sealed (not exposed to Earth atmosphere) to truly characterize their reactivity and toxicity. The regolith samples need to be kept distinct, so as to be able to interpret heterogeneity.

Both airborne and ground samples should be taken. Airborne dust may be quite different in overall properties from local martian soil. It may be more strongly activated by UV and radiation, and it may have a significantly different oxidation potential. As wind-blown dust is likely to be directly encountered by future human explorers, its toxic properties must be understood. You should get one airborne sample during a raging dust storm, one in nominal conditions, one superficially, “skimming” the surface, and at least 2 from different depths into the soil. The more samples, the less uncertainty in human health effects of the dust. We recommend pushing for at least 2 sites, 3 if possible to assess heterogeneity, and to improve confidence that the composition and reactivity issues have been bounded.

The grain size distribution of airborne dust would be of great interest for toxicology studies. Data on terrestrial dust shows that nano-size particles may have the highest toxicology potential. It is therefore important to determine the abundance of nanoparticles in airborne martian dust. This material may be higher risk to enter the habitat. Of note, the airborne sample would not tell much about the size distribution of the regolith as a whole, since that which is wind-swept would be skewed, although wind borne samples might be reasonable to evaluate for shape/angularity/surface area and composition. Having a small quantity of both windborne and scoop samples to compare would be informative.

A filtered sample of dust, as proposed, would be quite valuable, and probably quite adequate because it could be analyzed on a grain-by-grain basis --- a few ten thousands of grains would provide a lot of data. One problem is how to disconnect the filter from the pump or vacuum plenum, so it is a somewhat non-trivial task. The simplest engineering solution would be something like collecting dust on a passive filter via fallout, but if the mission is short, you may not get adequate sample. (The actual sampling strategy could be evaluated by the assigned project design engineers, and the most practical hardware recommended.)

B-Toxicity of martian dust

Unfortunately the evidence base for establishing the hazard associated with biological toxicity of Martian soil and dust is scant. The information currently available about putative life on Mars, either current or historically, is derived from preliminary *in situ* experiments conducted by the Viking lander, and from analysis of a Martian meteorite found in the Allan Hills region of the Antarctic ice fields^{3,4}. If life does exist on Mars currently, it is likely microbial, and is comprised of organism(s) somewhat adapted to extreme environments. The organism is likely not dwelling on the surface, but instead at a depth which is protected from surface radiation, has access, at least episodically, to liquid water, and under pressure >8 mbar. Whether more complex life once existed on Mars is a matter of intense scientific interest, which is a principle driver for exploration of the planet. Life more complex than terrestrial prokaryotes is improbable on Mars currently, however remnant organics from any historical life may be present in the soil/dust. These putative organics, in general, would pose low toxicity risk, however are molecules that scientists would want to be preserved for terrestrial analysis. Without complex lifeforms on Mars currently, the existence of martian microbial pathogens is very unlikely, as there would be no hosts for the microbes to adapt infectiously.

Biological toxicity of potential microbes on Mars can be broken into 3 categories: 1) irritative/allergic, 2) infectious, and 3) pathogenic:

Irritative- this is a minor form of toxicity, that would most likely to result in cutaneous or mucous membrane reaction (erythema, edema, pruritis, urticaria) from contact with the microbial surface antigens. A potentially serious, although rare reaction to microbial antigens could be anaphylaxis- from either inhaled, ingested, or hematogenous exposure of the human to the organism. Anaphylaxis, if not properly treated, can be fatal, due to laryngospasm. Irritative or allergic manifestations are expected to be the highest probability of human reaction to martian microbes.

Infectious- it is possible putative martian microbes could be infectious to humans, that is could survive and propagate inside the human body. If the organisms are motile, the likelihood of systemic distribution would be greater, however the human immune response to these putative organisms is at this point only speculative. It is possible, that should a martian microbe be able to avoid immune surveillance and survive inside a human body compartment, it may not produce any adverse affect on the host. They could co-exist with the host or less likely, be symbiotic.

Pathogenicity- even if martian organisms are infectious, it does not mean they would be pathogenic, i.e.- produce human disease. The number of highly evolved terrestrial microbes which can produce disease in humans, is quite small %-wise, and many of those are due to contact with elaborated (exo-) or inherent (endo-) toxins (e.g. botulinum, tetanus, etc.) and not due to the actual infection/invasion of the human body. Pathogenicity is extremely rare among extremophiles (autotrophs, lithotrophs, chemotrophs)³ as we suspect the martian microbes to be.

A very small dust sample should be set aside for use in assessing crude biologic toxicity, in both cell culture and a whole rodent models.

Planetary Protection- The prospect of Martian surface or subsurface life, together with the existence of a diversity of routes by which microbial pathogenicity has emerged on Earth, suggests that the possibility of human pathogens on Mars, while low, is not zero. In 1997 the National Research Council (NRC) Space Studies Board assessed the biohazard risk of putative Martian microorganisms as it relates to the issue of back contamination from a Mars sample return mission³. The report concluded that it is unlikely that putative Martian organisms would be capable of out-competing Earth organisms for nutrients, since Earth's microorganisms are optimally adapted to their environments as a result of billions of years of intense competition. Contamination of Earth by putative Martian microorganisms is thus unlikely to pose a risk of significant ecological impact or other harmful effects according to the study. The risk was not felt to be zero, however. Therefore, the board recommended that samples returned from Mars by spacecraft be contained and treated as though potentially hazardous unless and until sufficient knowledge of Mars and its environment becomes available. Since the discovery and study of Martian life can have long-term benefits for humanity, the risk that Martian life might include pathogens should not be an obstacle to human exploration; however, planetary protection must be considered. Both an agency planetary protection officer concurred biosafety protocol and appropriate laboratory BSL certification must be employed for the returned martian soil/dust sample³.

Discussion

No one on this medical/toxicity team is putting a Mars sample return in the critical path for human missions to Mars. However, sample return may significantly improve the hazard knowledge and thereby reduce uncertainty about the risk of human exposure. Characterization of the dust also would allow better design of systems for Mars surface operation, and human protection.

Issue- amount of regolith

It would be wise to exert some caution regarding the requirement for the amount of sample required for medical/toxicity assessment. A single sample return might not answer all the questions that a human mission might like to have under their belts. On the other hand, Safe on Mars and some NASA studies have concluded that sample return might not be necessary at all.

If we levy too many requirements on sample return, and SMD opts to go for a single attempt at such a mission rather than the series of 3 to 10 missions that have been recommended by scientists, then it would not be good to invent requirements that such a mission simply could not achieve. For example, obtaining regolith samples 1 km apart may be a completely arbitrary requirement, as MER, Pathfinder, and Viking all found what appears to be a very similar soil, planet-wide. Yet just meters apart, occasionally a significant signature from nearby rocks (e.g., high K-content at Pathfinder, and high P-Ti content for a couple of soils at Gusev) has been found, and the S and Cl contents can vary somewhat.

Likewise, the use of samples for biological testing in lieu of physical and chemical testing may be ill advised, since the returned samples could be analyzed for every conceivable hazardous element and compound- and thereby the hazard characterized significantly, without any biological tests. In a previous workshop held at Ames Research Center approximately 10 years

ago, the conclusion was that it might be necessary to expose tiny amounts of soil to cell cultures, and perhaps even to rodents.

Perhaps another way we should look at this is that our first Mars sample return mission would be the pioneer that could provide the capability to screen a future human landing site. If the human program decides that it needs large quantities of material to further characterize the risks, then the challenge would be to fund a dedicated mission for toxicity evaluation purposes, but the scientific rationale for large quantities of Martian soil cannot be defended if approached with the knowledge that we managed to go to a putatively hazardous moon with not a single grain of lunar regolith in hand, prior to the mission.

Issue- *sample return vs stimulant*

The team does not have confidence in our ability to develop a credible Martian regolith/dust simulant for toxicity testing purposes. The most compelling reason for this thinking is that we have been unable to do so for the lunar regolith. Part of the problem is that the natural lunar material begins to react with the Earth's atmosphere and particularly the moisture very quickly. This changes the essential properties. Even manufacturing grains of the right shape/mineralogy is very hard under Earth's conditions. Thus, this strategy might not be viable for IVA-5.

The challenge will be to find methods for both biohazard testing and toxicity testing to with smaller amounts of material. It is probably realistic on the latter to get down to 3 grams or less. The challenge should be equal for the laboratory analysis. Recommend developing a set of "requirements" for up-grading/improving our laboratory ability to analyze small samples. There was such a program in the 60s to prepare for the Apollo samples. The cosmic dust/Stardust sample analyzers are doing some of this (and keeping current with instrumentation) but there is likely a deficiency in many of the labs to obtain reliable data with small sample quantities.

Investigation Summary: Sample needs/priorities

Priority for first sample return: HIGH

Sample types required:

Pristine (preserved) dust sample

Regolith sample(s) beneath superficial deposits

Size fraction priority: <20 µm

Priority of samples from a second landing site: HIGH

References:

1) Lunar In Situ regolith study justification white paper:

“Crew Health & Performance Requirements for RLEP2 mission lander” Anthony Colaprete; Jeff Jones; John James; Tom Sullivan; Noreen Khan; David McKay; Antony Jeervajan; John Lindsay; Lawrence Taylor; Keith Manuel; Richard McCluskey; Russell Kerschman 2006

2) “Safe On Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface” National Research Council, National Academy of Sciences, National Academy Press, Wash. D.C. 2002

3) Warmflash, D, Larios-Sanz, M., Jones, JA, Fox, GE, McKay, DA. Assessing the biohazard potential of putative martian organisms for exploration class human space missions. ASEM 78(4) Section II suppl. A79

4) McKay DS GE, Thomas-Keprta KL, Vali LH, Romanek CS, Clemett SJ, Chillier ZD, Maechling CR, and Zare, RN. Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. Science 1996;273:924.

Investigation 3. Assess atmospheric electricity conditions that may affect TAO and human occupation.

Measurements:

a. Basic measurements:

- i. DC E-fields 0-80 kV/m, $dV=1$ V, bandwidth 0-10 Hz, rate = 20 Hz
- ii. AC E-fields 10 μ V/m – 10 V/m, Frequency Coverage 10 Hz-200 MHz, rate = 20 Hz, with time domain sampling capability
- iii. Atmospheric Conductivity 10^{-15} to 10^{-10} S/m, ds= 10% of local ambient value
- iv. Ground Conductivity $> 10^{-13}$ S/m, ds= 10% of local ambient value
- v. Grain charge $>10^{-17}$ C
- vi. Grain radius 1-100 μ m Combine with surface meteorological package to correlate electric forces and their causative meteorological source > 1 martian year, both in dust devils and large dust storms. Combine requirements for 1Bb with 3a above.

Investigation IVA-6: Implications for sample return.

Analysis Leader: Vicky Hipkin.

See discussion under IVA-2.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

1. dust sample

Priority of samples from a second landing site: LOW

Investigation 4. Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.

Measurements:

- a. Determine the rate of destruction of organic material by the martian surface environment.

- b. Determine the mechanisms and rates of martian surface Aeolian processes that disperse organic contaminants.
- c. Determine the adhesion characteristics of organic contaminants on landed mission elements, and the conditions and rates under which these contaminants are transferred to the martian environment.
- d. Determine the mechanisms to transport surface organic contaminants into the martian subsurface, and in particular, into a martian aquifer.
- e. Determine if terrestrial microbial life could survive and reproduce on the martian surface.

Investigation IVA-7: (Forward Planetary Protection) Implications for sample return.

Analysis Leader: Carl Allen.

The MEPAG-chartered Human Precursor Science Steering Group recently assessed the implementation of this Goal, and specifically Objective IV-A “Obtain knowledge of Mars sufficient to design and implement a human mission with acceptable cost, risk and performance.” (Beaty et al., 2005). This study recommended five medium-priority investigations, including “Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.”

This proposed investigation is associated with “Forward Planetary Protection” – the risk of terrestrial life transported to Mars. The concern focuses on local or widespread contamination of the martian surface, leading to possible false positive indications of martian life. The major questions concern (1) the survival and reproduction of terrestrial life on the martian surface and (2) the dispersal of terrestrial life or its remains on Mars (Beaty et al., 2005).

Can terrestrial life survive and reproduce on the martian surface?

Important questions for a human mission involve the survival and reproduction of terrestrial microorganisms on the martian surface. A key corollary is to determine the rate of destruction of organic material by the martian surface environment. Many details of these questions can, and should, be addressed in terrestrial simulation laboratories, rather than by deliberately placing terrestrial organisms on the martian surface.

Can terrestrial life, or its remains, be dispersed on Mars ?

This question addresses a wide variety of dispersal mechanisms, many of which are being investigated in the existing Mars science program and in recommendations from other groups. For instance, it would be important to determine the mechanisms and rates of martian surface aeolian processes which disperse organic contaminants. It would also be important to determine the mechanisms of transport of surface organic contaminants into the martian subsurface, and in particular, into a martian aquifer. A parallel study, currently being addressed by the Mars Technology Program Planetary Protection effort, seeks to determine the adhesion characteristics of organic contaminants on landed mission elements, and the conditions and rates under which these contaminants are transferred to the martian environment.

The level of forward contamination from a robotic lander could possibly be addressed by means of samples collected on Mars and returned to Earth. Specifically, the surface material in the vicinity of a lander could be sampled and assayed for evidence of biological contamination from

the spacecraft. This assay could be conducted in the vicinity of the Sample Return lander, or in the vicinity of a previous lander that might be visited to retrieve a sample cache. The following considerations apply to requirements for forward contamination assessment on a first sample return mission.

The minimum sample required for forward contamination analysis would be the soil and dust immediately downwind of the lander.

The sample for return to Earth must be minimally altered by the acts of collection and storage. Biological contamination must be kept below sampling hardware sterilization limits required by Planetary Protection (currently Viking-level sterilization). Organic contamination must be kept below Viking-level detection limits (1 ppb).

A single sample of soil and dust from close to the lander would be sufficient to conduct this investigation on a first sample return mission. The Draft Test Protocol (Rummel et al., 2002) states that 15 – 25 g would be sufficient to carry out all required biohazard testing. However, advances in the field of biohazard testing combined with targeted high-sensitivity testing for specific terrestrial organisms or their remains, might result in a requirement for considerably less material.

The environmental tolerance of many terrestrial organisms are unknown, so the sample should be preserved and transported in an environment as little altered as possible. Specifically, it should be kept at or near ambient pressure in a Mars-like atmosphere and at a temperature within the annual temperature range at the sampling site. The effects of exposure to environmental conditions outside of this range are unknown but could include death of viable organisms, alteration of organism remains, and alteration of chemical biosignatures.

The forward contamination sample should be collected using sterilized, precision cleaned sampling hardware. If more than one sample is collected, a separate implement to contact each sample preferred is preferred to prevent cross-contamination. Each sample should be placed in a sterilized, precision cleaned, sealable container.

The forward contamination sample should be selected based on its location adjacent to the lander. The spacecraft imaging system should be sufficient for sample selection.

The forward contamination sample should be collected in the immediate vicinity of the spacecraft. Lateral mobility on the order of 1 meter should be sufficient. The sample of surface material would not require vertical mobility beyond that of an arm-mounted scoop.

The forward contamination sample would be subjected to detailed analysis at the sub-micron scale. It must therefore be stringently protected from contamination from the sample handling equipment and from cross-contamination by other samples. The forward contamination sample must be stored in a dedicated container designed to remain intact and sealed until secured in the Sample Receiving Facility on Earth.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

1. dust sample

Priority of samples from a second landing site: LOW

Investigation 5. Characterize in detail the ionizing radiation environment at the martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.

Measurements:

- a. Measurement of charged particles with directionality. Identify particles by species and energy from protons to iron nuclei in the energy range 20-1000 MeV/nuc.
- b. Measurement of neutrons with directionality. Energy range from 1 keV (or lower) to 100 MeV (or higher).
- c. Simultaneous with surface measurements, a detector should be placed in orbit to measure energy spectra in Solar Energetic Particle events.

Investigation IVA-8: Implications for sample return.

Sample return would not significantly contribute to this investigation.

Investigation 6. Determine traction/cohesion in martian regolith (with emphasis on trafficability hazards, such as dust pockets and dunes) throughout planned landing sites; where possible, feed findings into surface asset design requirements.

Investigation IVA-9: Implications for sample return.

Overview: Most of the measurements called for in this investigation are properly conducted in situ and would require no sample return. Additionally, the requirement for this investigation is that the regolith properties are to be characterized “throughout planned landing sites” (referring to the future human landing sites). Without a concrete plan to send humans to the same landing site as a Mars sample return mission, it is not possible to accomplish this investigation with Mars sample return because the properties in question are known to be highly variable from one site to another. The only components of the human site we can hope to characterize with a Mars sample return are those that are globally ubiquitous – i.e., surface dust.

Mars sample return as it relates to the specific measurement requirements of this investigation:

- a) Determine vertical variation in in-situ regolith density within the upper 30 cm for rocky areas, on dust dunes, and in dust pockets to within 0.1 g cm⁻³. The vertical variation in in-situ regolith density in the upper 30 cm is likely to be strongly dependent on landing site location, thus there would be no value for sample return for this measurement unless we send humans to the same site. Even if humans were sent to the same site, the measurement would be of greater value if made in situ. Packing of the regolith from the sampling and return process could change its density as a function of depth. Also, a 30-cm long sample would likely not be feasible for Mars sample return.
- b) Determine variation in in-situ internal angle of friction of regolith for dust dunes and dust pockets to within 1 degree. This measurement would be best made under martian ambient environmental conditions (gravity, atmospheric pressure, and humidity) and in its original (natural) packing condition. It is usually inferred from looking at the sides of trenches made

by rover wheels or scoops. There would be no advantage in attempting to make this measurement on a sample returned to Earth.

- c) [Determine regolith cohesion for rocky areas, dust dunes and in dust pockets to within 0.1 kN m⁻²](#). This measurement also must be made in situ. For rocky areas, it would not be possible to bring back enough rocks to make this measurement on Earth because of mass limitations on returned sample. Even for dusty surfaces, the utility of the measurement would be much greater if it is made under martian ambient environmental conditions, with the regolith in its original packing condition.
- d) [Precision imaging to Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment \(MRO HiRISE\) standards \(30 cm/pxl\) for selected potential landing sites](#): Sample return would not be relevant to this measurement.

Mars sample return as it relates to measurement required for mobility systems:

The MEPAG goals also describe the following measurement requirements related to basic design of mobility systems: i) rolling resistance on wheels, ii) traction measurements for wheels, and iii) measurement of the shape and size of the wheel ruts that result from normal driving. All of these measurements are related to rovers traversing the martian surface, so measurements with returned samples on Earth would not be as useful as measurements made with robotic rovers on the Martian surface. It is possible that some utility could come from using the physical properties (e.g., distributions of regolith grain size and shape) of a small, representative sample of regolith to select a mechanical analog material from terrestrial sources to help in the design of mobility systems. However, such an investigation could easily “piggyback” on other investigations that require samples of the regolith.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

- 1. regolith sample(s)

Priority of samples from a second landing site: LOW

Investigation 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Measurements:

- a. [P, V, T, n, and dust density \(opacity\) as a function of time at the surface, for at least a Martian year, to obtain an understanding of the possible meteorological hazards inside dust storms. Surface Package measure directly:](#)
 - i. [Same as requirement for 1Bb with added](#)
 - ii. [Dust size 1-100 um](#)
 - iii. [Dust density 2-2000 grains/cc](#)
- b. [Orbiting weather station: optical and IR measurements to monitor the dust storm frequency, size and occurrence over a year, & measure terrain roughness and thermal inertia. Climate sounder would enable middle atmosphere temperature measurements. In situ density or](#)

spacecraft drag sensors could monitor the dust storm atmosphere inflation at high altitudes. Same as requirement 1Bc.

Investigation IVA-10: Implications for sample return.

Analysis Leader: Vicky Hipkin.

See discussion under IVA-2.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

1. dust sample

Priority of samples from a second landing site: LOW

Objective B. Conduct risk and/or cost reduction technology and infrastructure demonstrations in transit to, at, or on the surface of Mars.

Technology validation on Mars flight missions and infrastructure emplacements are needed to reduce the risk and associated uncertainty inherent in new, unproven technologies and to reduce the cost of human Mars exploration. These demonstrations were chosen for Mars robotic flight missions based upon: (a) their high degree of interaction with the Mars environment, (b) their anticipated large leverage on human Mars mission architecture feasibility, and (c) uncertainty of whether Earth, Earth-orbit or lunar testing would supply sufficient data to reduce risk and cost, or increase performance of these systems.

Analysis Leader: Noel Hinners.

Materials degradation. The concern is how materials emplaced and/or used on the martian surface may degrade due to 1. radiation; 2. thermal cycling; 3. erosion and physical abrasion; and 4. chemical reaction with the atmosphere or surface material. Materials degradation is a strong function of the specific material, its use and conditions of exposure (e.g., time, orientation). The radiation (UV, visible, proton, cosmic ray) could be well simulated based on what we now know about the radiation environment and what could be obtained from future in-situ radiation experiments. Thermal cycling could be adequately simulated based on our existing knowledge of the martian near-surface temperatures. Erosion and physical abrasion is a result of exposure to airborne dust (“sand blasting”), movement of materials on or over martian regolith (e.g., wheel coverings, boots and gloves) and grinding on moving surfaces (e.g., gears, motors). Analysis of the physical properties of returned martian regolith (e.g., angularity, hardness, size distribution) could provide much of the information needed to evaluate the potential for erosion and physical abrasion. This information could be used to develop a martian regolith stimulant that could be used in large scale engineering tests. There would be no need for a special “degradation” sample as long as representative regolith is obtained (i.e., not all pebbles). This argues for multiple (minimum 2) different regolith samples. The last factor, chemical reactivity, is a concern that could be addressed in part by analysis of the chemistry and chemical reactivity of returned samples, especially fines. This would require that the sample be acquired in its native environment and that it be preserved and thus represents pristine martian conditions.

The above indicates that analyses of returned sample could be of useful in understanding the potential for materials degradation in the martian environment. It is, however, not likely to be as definitive as desired by human exploration mission planners. This results from two factors: 1. returned samples would not indicate what short-lived, reactive chemical species created by photochemistry, for example, might exist in the atmosphere or that might be labile on soil particulate surfaces. 2. materials degradation may be a synergistic effect of multiple environmental factors acting in concert and which cannot be adequately simulated. For these reasons it was suggested in Goal IVB that coupons of materials be emplaced on the martian surface with the possibility of eventual return to earth. This would be analogous to the Long Duration Exposure Facility flown in earth orbit and retrieved by a Shuttle flight. An “all-up” Mars-LDEF would likely be a major robotic mission element in terms of size, mass, manipulation and packaging. It might also be possible to instrument a Mars-LDEF to determine degradation properties without return of the materials. Such would be an ESMD mission and not a goal for an SMD sample return mission. Given that, however, we should consider that it may be feasible to attach small material coupons to sampling equipment (e.g., containers) sent on a sample return caching mission with an inherent multi-year exposure on the martian surface. Similarly, it might be plausible to include material coupons on other robotic missions (e.g., rovers) placed where they could be examined by instrumentation on the vehicles.

Investigation Summary: Sample needs/priorities

Priority for first sample return: LOW

Sample types required:

1. manufactured materials that have been exposed to the martian environment for known lengths of time.

Priority of samples from a second landing site: LOW

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