**The Astrobiology Field Laboratory**

September 26, 2006

Final report of the MEPAG Astrobiology Field Laboratory Science Steering Group (AFL-SSG)

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During the course of the SSG several breakout groups were formed to answer specific issues related to our discussions. These are as follows;

AFL subcommittees

**Sedimentary sub-team**. Pan Conrad, leader.

**Hydrothermal sub-team**. David Blake, leader

**Ice sub-team**. Luther Beegle, leader

**Sample preparation sub-team**. Jan Toporski, leader

**Definitions sub-team**. Pan Conrad, leader

**Instruments sub team.** Will Brinkerhoff leader

**Water sub-team**. Jan Amend, leader

# EXECUTIVE SUMMARY

The AFL SSG was asked to develop an analysis of a possible future mission called the **Astrobiology Field Lab**. This mission is a generic concept, consisting of a lander equipped with a major in-situ laboratory capable of making significant advancements towards MEPAG’s Goal I (“Determine if life ever arose on Mars”). In essence, the purpose of this analysis was to evaluate the question, “what is the most that can be accomplished in this area by in situ means?” In order to give the analysis team room to work, financial and timing constraints were very loose. Although at the time of convening this exercise 2013 was the closest discussed deadline and so considerations were given to what technically could be accomplished for this deadline.

The AFL SSG considered the problem at several levels:

What overall programmatic exploration strategies are needed to achieve Goal I? Results from many missions will contribute to these strategies, and a mixture of ambiguous and definitive outcomes will need to be accommodated.

What result would AFL need to deliver to make a meaningful contribution to this strategy?

What are the engineering options for configuring a landed mission that would make such a contribution?

Programmatic exploration strategies

In order to plan missions during the period 2013-1018, it is necessary to predict the state of human knowledge at that time. Although this is hard to do in detail, it is possible to reach some important generalities. First of all, habitability is the potential of an environment (and applied to either the past or the present) to sustain life. By this definition, habitability will be the integrated and accumulated knowledge of many missions and many different kinds of scientific investigations. However, as with any other potential, it will not be possible to achieve certainty unless life itself is discovered. Habitation, on the other hand, is a simple yes-no question. A key planning question, therefore, is when has the habitability potential risen high enough that a habitation test can be justified?

Although it has been generally assumed in the past that these two objectives need to be pursued sequentially, the AFL SSG has concluded that organisms and their environment together constitute a system, and each produces an effect on the other. Many kinds of investigations of this system can simultaneously provide information about both. This implies that habitability and habitation can be investigated together. This expands significantly on the current mission concept for MSL, with AFL having an expanded instrument suite dedicated more towards life detection and precision sample handling than MSL. Moreover, the process of life detection on Mars involves two sequential steps: 1). Proposing that a set of phenomenon are, or could be, biosignatures. This will constitute a working hypothesis that life is or was present. 2). Establishing that at least one of these biosignatures is definitive. This requires extensive effort and careful planning and a number measurements mutually confirming each other. Finally, we know that some kinds of scientific investigations will measure signs of both extinct and extant life without needing to distinguish between these two possibilities before launch.

Given the expected state of our knowledge about Mars during the period 2013-2018, the AFL SSG has reached three conclusions:

It is both possible and reasonable to do life detection first, then determine whether it is extinct or extant on the basis of a positive result.

Missions during this period can reasonably begin the process of life detection by characterizing potential biosignatures.

It is reasonable to set mission objectives that relate to both habitability AND habitation. It is not necessary to choose one at the expense of the other.

Finally if a definitive biosignature is located by AFL instrumentation and missions must be configured to definitively characterize that life signature. It is only by thorough study of a positive signal will skepticism be kept to a minimum and the maximum understanding of how this relates to the formation of life on earth be understood.

Engineering options

The AFL SSG has concluded that the following overall scientific objective is both achievable by AFL as early as 2013 (although 2018 was also postulated as a target from the pathways document, Figure 1), and is a significant extension of currently planned missions:

**For at least one Martian environment of high habitability potential, quantitatively investigate the geological and geochemical context, the presence of the chemical precursors of life, and the preservation potential for biosignatures, and begin/continue the process of life detection.**

By targeting an environment of high habitability potential, a response to prior discoveries is implied. Investigating the context is a reflection of the reality that our understanding of habitability will not be complete by 2013 we need to plan for more work. Understanding prebiotic chemistry is necessary to allow planetary-scale life-related predictions, especially in the contingency that life is not found in a specific experiment. Understanding preservation is key to interpreting the results of biosignature investigations, and is also critical feed-forward to future missions. Finally, life detection, as AFL SSG defines it, is a process that will take time. It is reasonable to expect that missions like AFL will play a significant role in this process, but unreasonable to expect that they will bring it to a conclusion.

Engineering options for an AFL mission

The AFL SSG has defined a landed mission that can achieve the above objective. There are multiple possible variations of what could be called “AFL”, and different scientists see these variations in different context, and with different systems of priority. However, it is possible to define an invariant base that is common to most versions, along with a discovery-responsive and competition-responsive cap. The basic landed system needs to be able to accomplish four things:

Acquire the right samples (access a place with high general habitability potential, understand preservation potential, have a high ability for scientific sample selection, capable sample acquisition system)

Know the context (Setting, mineralogy, chemistry, relationships)

ID best place on the sample (Mid-scale observations.

Precision sub-sampling (down to mm scale) for investigation by analytical suite)

At least 3 mutually confirming A/B measurements (Suites of observations by different means of the same or related phenomena will be necessary to reach definitive conclusions).

Initial engineering concepts for this mission place AFL as a COSPAR level 4B mission.

# 2.0AFL CHARTER

The AFL SSG was given the following charter.

Introduction

The Mars Program Office at NASA HQ (Code S) requests a study of the preliminary scientific options and engineering characteristics of the AFL mission. This mission was identified in the final report of the MSPSG (Mars Science Program Synthesis Group).

Starting assumptions (to be refined)

Assumptions for each mission need to be compiled separately.

Assume TBD mission must be ready to launch as early as TBD.

Science priorities will be derived from the MEPAG Goals document.

Requested Tasks:

Develop a set of candidate whole mission concepts. For each:

Define preliminary general science objectives, and science floor (the level below which the mission is not worth flying).

Identify and evaluate the primary science trades

Determine whether instruments capable of addressing the science objectives are likely to be available in time.

Landing site accessibility: Propose the size of the latitude band which needs to be held open for this mission, the landing precision, and required ability to land in rough terrain

Identify possible facility subsystems related to sample acquisition and sample preparation.

Describe the essential engineering constraints on the mission

Determine if positioning in the pathways makes a difference to the science/engineering of the mission.

Describe how the mission fits into NASA’s long-range strategic framework for the exploration of Mars

Based on the above analysis, present a prioritized set of preliminary options for consideration by NASA HQ.

Methods

The SSG is asked to conduct its business primarily by telecons, e-mail, and or web-based processes. There is enough budget to convene 1 or 2 face-to-face meetings.

Logistical support will be provided by the Mars Program Science Office.

Timing

It is expected that the team will be ready to start its deliberations in mid-November.

A mid-term telecon status check by Jim Garvin, Dan McCleese, and Bruce Jakosky is requested after the new year.

The near-final report of the AFL SSG is requested by Feb. 28, 2004.

It is expected that the results of this study will be presented to MEPAG at its June, 2004 meeting. Feedback from this discussion will be incorporated in the final report, which will be due July 31, 2004.

Report Format

It is requested that the results be presented in the form of both a PowerPoint presentation and a white paper. Additional supporting documents can be prepared as needed. After the white paper has been accepted by program management (including the MEPAG executive committee), it will be posted on a publicly accessible web site.

The report should not include any material that is a concern for ITAR (as is true of everything done by MEPAG).

Note, the bulk of this work and the draft white paper was completed by September 2004. There have been unavoidable delays to its publication. In the meantime thinking about AFL has progressed. This document reflects the thinking in September 2004. Whilst engineering and programmatic changes have occurred since then, the strength of this document lies in the science definition for the mission.

# DEFINTIONS

During the course of the AFL-SSG discussions several questions related to the MSPSG statement arose. Specifically these questions relate to the definitions of, for example, the terms habitability (or what constitutes a habitat) and biosignature. Critical questioning by the group resulted in the formation of a definitions subgroup

The following definitions were decided upon by that group. These definitions are consistent through this document and although we cannot suggest the wider community adopt these definitions it is suggested that some consensus within the MEPAG members is reached to prevent numerous iterations of this process in other reports.

Abiotic Chemistry

Mainly carbon based chemistry the speciation and composition of which has remained simple with the production of all different isomeric possibilities and show no chiral or species preferences. In this scenario complex molecules may only be kerrogenous in nature (type iv) and similar to that found in meteorites.

Biosignature

Any phenomenon produced by life (either modern or ancient). Two sub-definitions: Definitive Biosignature: A phenomenon produced exclusively by life.  Due to its unique biogenic characteristics, a definitive biosignature can be interpreted without question as having been produced by life. Potential Biosignature: A phenomenon that may have been produced by life, but for which alternate abiotic origins may also be possible.

Extant life

General reference to living or recently dead organisms which may also possess a fossil record.

Extinct life

General reference to past life (and no longer present on the planet). If evidence remains, it is ONLY fossil.

Habitability

A general term referring to the potential of an environment (past or present) to support life of any kind. In the context of planetary exploration, two further concepts are important: Indigenous habitability is the potential of a planetary environment to support life that originated on that planet, and exogenous habitability is the potential of a planetary environment to support life that originated on another planet.

Habitat

An environment (defined in time and space) that is or was occupied by life.

Life detection

The process of investigating the presence of biosignatures (including potential biosignatures). Life detection can apply to either past or present life.

**Micro BioSensors (not to exclude organic chemical detection)**

Miniaturized instruments or instrument suites that are developed from technology such as Micro Electronic Machine Systems (MEMS), Micro electronic optic systems (MEOS), Microfluidics, Micro Total Analytical Systems (uTAS) or Lab-on-a-Chip (LOC).

Prebiotic Chemistry

Mainly carbon based chemistry the speciation and composition of which has a complexity and has produced a number of polymeric systems that could be used for structural, metabolic processes and information storage and retrieval.

Present life investigation

One that specifically targets living or recently dead organisms. Time resolved studies on seasonal and daily (with perhaps higher frequency) time scales may be required to confirm observations that a biosignature of present life has been detected.

Preservation Potential

The potential for a particular biosignature to survive and therefore be detected in a particular habitat.

Primary Sample

Geological material (e.g. rock, regolith, dust, atmosphere, ice) acquired from its natural setting on Mars.  Note: specific locations where data are collected by contact instruments are referred to as "targets", not samples.

Secondary Sample

Any sample derived from the primary, including splits, extracts, sub-samples, etc.

# 4.0INTRODUCTION

The primary science driver for the mission concept was to define the first Mars mission to concentrate fully on Astrobiology science goals (as defined within the recently updated Astrobiology roadmap). Therefore, to define the preliminary general science objectives, and the science floor, the level below which the mission is not worth flying. The Astrobiology Field Lab was created as a concept by the Mars Science Program Synthesis Group (MSPSG) during their Pathways planning discussions in 2002-03 and can be paraphrased as;

**Astrobiology Field Laboratory.** “This mission would land on and explore a site thought to be a habitat. Examples of such sites are an active or extinct hydrothermal deposit or a site confirmed by MSL to be of high astrobiological interest, such as a lake or marine deposits or a specific polar site. The investigations would be designed to explore the site and to search for evidence of past or present life. The mission will require a rover with “go to” capability to gather “fresh” samples for a variety of detailed *in situ* analyses appropriate to the site. *In situ* life detection would be required in many cases.” (*From MSPSG (2003)*

However, MSPSG deferred to a successor team (AFL-SSG) the definition of AFL’s specific scientific and engineering constraints, possibilities, and priorities. The AFLSSG team was initially convened in October 2003 and operated through a number of telecons and one face to face meeting. Therefore this team was asked to plan during a constantly shifting science focus and have constantly endeavored to keep abreast of the Mars Exploration Rover findings and review the goals and outcomes of the SSG accordingly. Undertaking this activity at a time when 3 new space craft have started to explore Mars has been exciting, inspiring and already produced new evidence to which we have responded. Many notions of how to perform this mission have therefore been updated from preconceived notions held before specifically, the MER data was returned. We hope that these changes reflect a renewed sense of optimism and realization of the location of interesting samples to interrogate with instrumentation currently under development.

# 5.0SCIENCE GOALS

## 5.1 Assumptions

To undertake this task the AFL-SSG was asked to consider the following assumptions;

Assume AFL will need to be ready to launch as early as the 2013 opportunity

Assume all missions scheduled before 2013 are successful.

The MSL entry-descent-landing (EDL) system has successfully been demonstrated, and the engineering heritage can be used on AFL.

Assume the primary goal of AFL is to make a major advance in astrobiology.

Assume a cost cap approximately equal to that of Ground Breaking Mars Sample Return.

These assumptions are based on the timeline suggested by the Pathways SSG, summarized in Figure 1.

Figure 1. A summary diagram of the pathways proposed by MSPSG.

Generated

From Figure 1 it can be seen that the pathways leading to AFL are propelled by the discoveries of hydrothermal habitats and the search for evidence of past life. During the course of the AFL-SSG discussions several questions related to the MSPSG statement arose. Specifically these questions relate to the definitions of, for example, the terms habitability (or what constitutes a habitat) and biosignature. Critical questioning by he group resulted in the formation of a definitions subgroup the results of which are shown in Section 2.

Responses to discoveries other than pathway to discover hydrothermal habitats as shown in Figure 1 were deemed necessary and led to the formation of the hydrothermal, ice, sedimentary and water subgroups. Through these discussions the parallel nature of exploration and engineering goals in different environments was explored and a “core” of similar themes and objectives arrived at that included life detection philosophy, measurements, rover capabilities and sample preparation. This notion is explored further in section 8.1.2.

Other questions arising from the MSPSG guidelines and our discussions related to “the capability to gather fresh samples” which led to the formation of the sample preparation subgroup. The mention of *in-situ* life detection led to the Instrument subgroup surveying and documenting the current instruments in development.

Several assertions for the completion of these science goals were formulated and are as follows:

1.By 2013 a full model of the potential habitability of Mars, organized by environment, and applicable to both the present and geological past will be partially understood. Therefore the Mars program will have to choose to either; select one environment with a high habitability potential and test for habitation *or* continue to refine the habitability models to allow better targeting of a subsequent habitation mission.

Therefore we forecast one of two conditions will be true in 2013:

•More likely: Models of habitability require either further definition or further confirmation before a specific test for habitation should be attempted.

•Less likely: At least one environment (past or present) with high habitability and preservation potential has been identified, and a habitation test is justified.

We therefore questioned whether AFL would be effective in both scenarios. Which further reinforced the concept of defining a core set of mission parameters (Section 8).

2.Organisms and their environment together constitute a system. Each produces an effect on the other. Some kinds of investigations can simultaneously provide information about both the environment (e.g. habitability potential) and associated life forms (habitation).

3.Traditional Mars mission planning has involved choosing scientific objectives and investigations for EITHER prebiotic chemistry, extinct OR extant life. (PP policy is structured the same way.) However, some kinds of scientific investigations will detect all of the above categories and potentially measure the signs of life without prior need to assume search parameters that will pre-categorize whether it is extant or extinct.

4.As our exploration of Mars (through robotic and sample return missions and terrestrial studies on Martian meteorites) proceeds, anomalous features will be discovered that are POSSIBLE biosignatures for Martian life forms. It is important that this

Observation of POSSIBLE biosignatures can be made by relatively simple observations (e.g. geological, textural, geochemical). Such features would constitute a working hypothesis, **NOT** confirmation that life exists and has been detected.

Concluding that evidence of a Martian life form (past or present) has been discovered requires proving that a POSSIBLE biosignature was produced by the activities or remains of Martian life. Unless a POSSIBLE biosignature is proven to be a DEFINITIVE biosignature – an object or phenomenon that could only have been produced by life – it may not possible to prove the presence or former presence of life on Mars using AFL alone. However, the AFL mission has been configured so that it will not miss POSSIBLE biosignatures if they occur in a similar habitat and with similar character to those found on Earth and may indeed detect those non-earth centric signatures that would, without prior knowledge of the state of an unknown biochemistry, appear to be reasonably measurable.

Once several POSSIBLE biosignatures are identified, additional efforts will need to be made to prove that they definitively represent extant life or former life, or determine whether the group of POSSIBLE biosignatures is CONSISTENT with the hypothesis that life exists or once existed on Mars.

The current MEPAG goals document highlights the following strategy for Goal 1 “The search for Life” Determining if life ever arose on Mars is a challenging goal. *The essence of this goal is to establish that life is or was present on Mars,* ***or*** *if life never was present to understand the reasons why Mars did not ever support its own biology. A comprehensive conclusion will necessitate understanding the planetary evolution of Mars and whether Mars is or could have been habitable and will need to be based in multi-disciplinary scientific exploration at scales ranging from planetary to microscopic. The strategy we have adopted to pursue this goal has two sequential aspects: Assess the habitability of Mars (which needs to be undertaken environment by environment), and in environments which can be shown to have high habitability potential, to test for prebiotic processes, past or present life. These constitute two high-level scientific objectives. A critical means to achieve both of these objectives is to characterize Martian carbon chemistry and carbon cycling. The science associated with carbon chemistry is so fundamental to the overall life goal that we have established it as a third primary science objective. To some degree, these overarching scientific objectives can be addressed simultaneously, as each requires basic knowledge of the distributions of water and carbon on Mars and an understanding of the processes that govern their interactions.*

Importantly this statement points out that the seemingly differing goals, habitability, Carbon chemistry and the search for biosignatures, overlap and can therefore be addressed to a significant degree by the interpretation of measurements undertaken by certain instruments. Examples, habitability demands the presence of Carbon, biosignatures are often Carbon based etc. Amino acid analysis, n alkane distributions, selection of informational and catalytic polymers based on a narrow range of particular molecules and isomers of a particular molecular group. For example nucleic acids contain ACTGU on earth, but may contain LMNOP on Mars, it is the presence of a narrow range of the possible purines and pyrimidines available through abiotic processes that would constitute a biosignature. This could be true of any potential novel biomolecule and it *may be* that upon detecting a small range of the possible isomers of a particular compound speculation as to their informational or catalytic roles can begin.

Therefore AFL can reasonably begin the process of life detection by characterizing potential biosignatures.

## 5.2 Objectives

Proposed overall scientific objective of AFL:

For at least one Martian environment of high habitability potential, further investigate the potential for habitability, the potential presence of the chemical precursors of life, the potential for preservation of biosignatures, and possible signs of life.

This objective must balance the need to be a significant extension beyond currently planned missions, yet not an unrealistic extension of current technology. The detailed objectives proposed include (in no order of importance);

1.Within the region of Martian surface operations, identify and classify Martian environments (past or present) with different habitability potential, and characterize their geologic context.

2.Quantitatively assess habitability potential.

Measure isotopic, chemical, mineralogical, and structural characteristics of samples, including the distribution and molecular complexity of carbon compounds.

Assess biologically available sources of energy, including chemical and thermal equilibria/disequilibria.

Determine the role of water (past or present) in the geological processes at the landing site

3.Investigate the factors that will affect the preservation of potential signs of life (past or present) on Mars

4.Investigate the possibility of prebiotic chemistry on Mars (including non-carbon chemistry)

5.Document any anomalous features that can be hypothesized as POSSIBLE Martian biosignatures. This will constitute a set of working hypotheses, which will need refinement and further testing on Mars or in return samples.

### 5.2.1 Habitability

A definition for habitability is contained in section 2. From the first assumption above the following recommendation was made:Habitability models have the potential to integrate many different classes of information that have been made recently and will be acquired over the next decade. However, they will be most effective if placed on a semi-quantitative footing (see Appendix II for an example).This question was then followed up in discussions within the definitions subgroup and illustrated by Figure 2.

Habitability should be described by measurable parameters that index the potential of an environment to support life. Only in this way can the scientific community achieve consensus regarding whether or not a given environment is habitable, either for Martian or Earthly life. For any living system, certainly there will be a range of environmental requirements, outside of which life will be unsupportable. Even though we have no information on potential Martian biological requirements, we can learn from universal Earthly life requirements. The AFL study group has agreed that Earth life requires water and certain chemical raw materials such as carbon, hydrogen, nitrogen, phosphorus and a few others in trace amounts (Williams and Fraústo da Silva, 1996). We also know that life makes products from these raw materials with the additional requirement for an energy source, so sufficient habitat space must be available for the products to be mobilized or diffuse away, otherwise metabolic reactions would run to equilibrium, or possibly reverse. On Earth, the chemistry of life involves oxidation-reduction reactions, and metabolism from the archaea to some highly-evolved eukarya requires electron donor/receptor pairs. The spatial distribution of both oxidized and reduced forms of ions involved in respiration may be as important as their concentration in the context of biological requirements.

We assume that the astrobiology community will have made progress toward consensus regarding the indexing of habitability before the launch of an AFL mission, as the concept of habitability will have an impact on missions with the scope of Terrestrial Planet Finder to SSE missions in search of present or past Martian habitable environments. One approach toward such progress may lie in development of terms that lead to a probabilistic evaluation—a scale of habitability based upon measurements of agreed-upon parameters such as threshold concentrations of water and other raw materials, energy, etc.

### 5.2.2 Extinct or Extant Life. Abiotic or Prebiotic Material

It is important to recall that life on Mars may be composed of many molecules that differ from those of Earth life. However, most current hypotheses on extraterrestrial life maintain that Martian life, if it exists or once existed, will resemble life on Earth in that it will be: 1) composed of carbon, 2) based on a ‘nucleic acid like’ replication mechanism and 3) packaged in cellular compartments. Measuring the distribution, isomerization and quantities of carbon species limits the search to life based on carbon chemistry, an appropriate goal that reflects the strategies used to locate the biosignatures of ancient carbon-based life forms on Earth. Potential organic carbon species that would need to be distinguished by AFL are given in Table 2.

In the search for biosignatures on Mars the interpretation of measurements will determine whether a particular results indicates the category to which a particular a/biosignature should be placed i.e. pre/abiotic extinct or extant. The important issue is to make the correct measurements to ensure the sensitive detection of molecules of interest can be undertaken.

Figure 2 Illustrated the cross cutting relationships between the searches for habitability in comparison with the search for evidence of past or present habitation.

From assertions 2 and 3 and illustrated by Figure 2 the implications are that***:***The distinctions between investigations of habitability potential, habitation, extinct life, and extant life are blurred. It is possible to configure a mission that has relevance to ALL of these subjects.

Without evidence of liquid water on Mars, the potential to locate extant Martian life is less, as all conceivable life forms require liquid water. Hence the focus of upcoming missions on determining whether liquid water is available. Until this information is known, an AFL mission will need to be prepared to detect both extinct and extant life, as well as be able to distinguish abiotic and prebiotic material. We assume that the investigation of abiotic and prebiotic chemistry will be useful in evaluating the postulated meteoritic and cometary delivery of exogenous organics to the lithosphere and the formation of organic material by indigenous hydrothermal processes. The current MER information that Mars harbors environments that contained liquid water in the past indicates that the possibility of discovering extinct life has increased.

All information gained from AFL will be useful with regard to either describing what kind of life exists/existed on Mars or describing conditions found on Mars and determine why life evolved on Earth and not Mars (assuming the conditions on Mars are similar to those on Earth). The search for the signatures of prebiotic chemicals or components of life–past or present will provide important information that will advance the field of astrobiology and the understanding of our own planet. In addition, there is now considerable evidence pointing to the presence of methane in the atmosphere on Mars (Kerr 2004a.b commentary). This implies that geological processes on Mars could provide a chemical potential and carbon source that could be used by microorganisms and may indicate the presence of hydrothermal sites and liquid water. The generation and fate of atmospheric methane on Mars would be a significant goal for missions that fly prior to AFL. Such measurements would significantly improve our understanding of habitability.

Investigating early planetary surface chemical processes on Mars is important to understanding two possible program-level exploration outcomes:

If life is not present at a specific test site, can we predict that it might exist elsewhere?

If life never formed on Mars, WHY?

Studying such issues will also address specific goals, issues:

Understand planetary evolution through elucidating organic chemical input i.e. meteoritic versus abiogenic synthesis reactions.

Mars may give clues to the prebiotic evolution of the Earth. On Earth an unaltered geologic record of early planetary evolution (4.5-3.8 Ga) does not exist.

Allow conjecture as to why life did not start on Mars (should that be the outcome). Were the chemical processes and building blocks present there as on Earth?

By definition, a biosignature is an indicator of life or biological activity. Therefore, by definition, the discovery of even one biosignature on Mars would indicate that life once existed on the red planet. However, discoveries of ancient POSSIBLE biosignatures on Earth and Mars have shown that it can be extremely difficult, if not impossible, to prove their biogenic origin. Our inability to prove an object or phenomenon’s biogenic origin (i.e., biogenicity) is hampered by the fact that inorganic processes can produce abiotic mimics of biosignatures. Hence the need to make a distinction between a POSSIBLE biosignature and a DEFINITIVE biosignature.

A DEFINITIVE biosignature is one that has attributes that can ONLY be produced by life or biological activity. Until such time that a POSSIBLE biosignature is proven to be a DEFINITIVE biosignature, the former constitutes a working hypothesis that requires additional characterization. AFL will contain the necessary equipment to detect POSSIBLE biosignatures (e.g., microfossils, biofabrics, biominerals, biomarkers, biomolecules isotopes, etc.). However, short of locating a living or perfectly preserved cell that displays the structural complexity indicative of biosynthesis, establishing that a POSSIBLE biosignature is DEFINITIVE evidence for life will require further testing. It will also be necessary to prove that a biosignature is indigenous to Mars and not a contaminant, regardless of whether we discover it on Mars or in rocks or sediment returned to Earth from a future sample return mission from Mars. These considerations underscore the need to distinguish a DEFINITIVE biosignature from a POSSIBLE biosignature. This underscored the goal of the definitions sub group that postulated that only by producing several mutually supporting lines of evidence (i.e. possible biosignatures) could a definitive biosignatures be postulated.

The lack of a conclusive set of criteria for life detection and preservation has been illustrated recently by two debates; the search for the oldest evidence of life on Earth and the raging debate on the claims for life in ALH84001 (McKay, 1996). The scientific controversies over the former debate, that of the earliest evidence of life on Earth, have recently intensified but are still unresolved (Schidlowski, 1988; Schopf, 1993; Mojzsis et al., 1996; Rosing, 1999; Mojzsis and Harrison, 2000; Brasier et al., 2002; Fedo and Whitehouse, 2002, Pasteris and Wopenka, 2003, Furness 2004). The common denominator in both of these debates is the underlying difficulty, or inability to demonstrate conclusively the biological origin of the respective evidence, which in either of the above cases would have to be seen as conclusively proving the presences of fossil microbial life. However, a consensus that has emerged from these discussions, and is now seen as a critical requirement, is the demand for further lines of evidence in addition to any morphological data that supports such extraordinary claims. Since the inception of the second debate, that of life in Martian meteorite ALH84001, it has become evident that there is no consensus on the nature of life in extraterrestrial materials. Indeed techniques supposed to detect life failed, for whatever reason, to conclusively detect the presence of terrestrial organisms within this meteorite (Steele et al., 1999, 2000, Toporski, 2000). Recent studies suggest that the mass spectrometry experiments on the Viking lander would have missed 3x107 bacteria per gram of Martian regolith (Glavin et al., 2001). These examples are beginning to show that only by means of a multi-disciplinary, multi-instrument scientific approach, will the above questions be answered. It is clear that a great deal of additional systematic experimentation and testing must be undertaken in terrestrial environments to better determine the criteria by which biogenicity and therefore preserved biosignatures can be quantified.

Though there are a number of ways of categorizing biosignatures, microbial biosignatures found in ancient Earth rocks can be organized into three categories: *bona fide* microfossils, microbially influenced structures, and chemical fossils, also known as chemofossils (Cady et al., 2003). Bona fide microfossils, which may include cellular and/or extracellular remains (e.g., carbonaceous microfossils), display structural and chemical characteristics that confirm their biological origin. Microbially influenced sedimentary structures (e.g., biogenic stromatolites and microbialites), display biofabrics and morphologies known to have been produced by the presence and/or activity of biofilms or microbial mats. Chemofossils (e.g., biomarkers and biominerals), display chemical, isotopic, and structural characteristics indicative of biological activity.

Among the chemical biosignatures that have been identified as applicable to past and present biological activity on Earth are the biominerals, that is, minerals formed by biotic processes, either directly, or indirectly. Biominerals have been found in the fossil record that date back to the Precambrian. It has been suggested that biominerals could be important indicators of life and thus could play an important role in the search for past or present life on Mars (Schwartz et al., 1992, Cady et al 2003). Furthermore, organic components (biomarkers) that are often associated with biominerals are believed to play crucial roles in both pre-biotic and biotic reactions. For measurements carried out on Mars, a crucial step will be the in situ quantification of the nature, structure and concentration of biosignatures as a function of depth and time.

The search for biosignatures requires an extensive knowledge of the context in which they are found. The types of rocks and paleoenvironments that have the highest potential to trap and preserve biosignatures on Earth and Mars include: mineralized sinters, evaporite basins, mineralized soils, subsurface sedimentary systems, permafrost and ground-ice (Farmer and Des Marais, 1999). Recent data from the Mars orbiter, which suggests the presence of reduced gases of biological or volcanic origin, indicate that gas seeps in any type of terrain should also be targeted for possible biosignatures. On Earth, additional criteria such as tectonic setting and alteration history are taken in consideration when looking for biosignatures. The amount of alteration a deposit has experienced since its time of formation is particularly important for assessing the preservation potential of a deposit (see next section).

Typical lithologies for searching for biosignatures of past life in ancient terrestrial settings are similar to the ones we hope to find on Mars. Interestingly the haematite rich sites like those found by the MER rovers at Meridiani and Gusev may not be the ideal sites to search for Carbon signatures due to the poor preservation of organic material in haematite (Sumner 2004). Settings with a higher preservation potential include aqueously deposited chemical sediments, such as cherts, carbonates, or phosphates, which are known to be effective at preserving biosignatures on Earth. Because the spatial scale or distribution of such deposits on Mars is presently unknown, and because of the difficulty of resolving mineral mixtures using available or recently acquired remote spectral data (i.e., TES, THEMIS or CRISM), the acquisition of data at high spatial resolution (30-100m/pixel) from selected locations is considered a crucial precursor to defining an adequate landing site for the AFL mission.

A critical component for identifying biosignatures on any planetary body is the ability to assess in-situ the potential for an aqueous geochemical environment to create and support life. As an example for Mars, in-situ characterization could provide evidence as to whether the chemical composition of the evaporites located in suspected ancient water bodies were biologically influenced or possessed the chemical parameters within which life may have existed, or may still exist.

It is almost certain to be the case that any life signature found on Mars will become the basis for intense debate and necessary follow up investigations. These investigations must be targeted at characterization of any positive signal.

If investigations prove negative for all forms of carbon / biosignatures then spatially resolved measurements must be undertaken to different sites to ensure all reasonable target areas have been explored.

**Table 2**. Possible sources of organic carbon that need to be distinguished in Martian samples.

|  |  |
| --- | --- |
| **Source of Carbon** | **Carbon compounds. examples/comments** |
| Abiotic molecules from meteoritic / cometary influx | Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, sugars and sugar derivatives. |
| Prebiotic/abiotic molecules from synthesis reaction process on Mars | Amino acids, purines and pyrimidines, polycyclic aromatic hydrocarbons, chain hydrocarbons, fatty acids, sugars and sugar derivatives. |
| Terrestrial contaminating organics | Condensation products derived from rocket exhaust, lubricants, plasticizers, atmospheric contaminants |
| Terrestrial contaminating organisms | Whole cells, cell components (LPS, DNA, proteins, cytochromes) found on AFL itself. |
| Terrestrial like organisms – from Earth | Organisms not present on the craft measuring them, but had been previously transferred from Earth by either meteorite impact or contamination of previous spacecraft. Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions |
| Terrestrial-like organisms – evolved on Mars | Organisms that utilize terrestrial like biochemistries and have evolved on Mars Target molecules could include individual genes, membrane constituents, specific enzymes, and co-enzymes that would be expected to be over expressed or adapted in Martian conditions or organisms using metabolisms that would not be present on a space craft contaminant such as methanogens, psychrophiles endolithic survival mechanisms. |
| Non-terrestrial-like organisms | Utilizes an array of molecules for information storage, information transfer, compartmentalization and enzymatic activity that differ from those used by extant terrestrial life. Examples would be the use of novel amino acids and nucleotides or the use of novel nitrogen utilization strategies. |
| Fossil biomarkers | Detection of established terrestrial fossil biomarkers such as hopanes, archaeal lipids and steranes, for the detection of the diagenetic remains of terrestrial based life. Characterization of potential breakdown products that can be reasonably extrapolated from the detection of molecules comprising an extant Martian life form. Detection of the diagenesis products of extinct Martian organism based on carbon compositions consistent with biological fractionation of a narrow range of abiotic precursors. |

#### 5.2.2.1 What techniques have been used to detect and characterize terrestrial and meteoritic biosignatures?

1. Morphological observation using microscopic tools (Light, SEM, TEM, AFM, Fluorescence). The controversy mentioned earlier regarding the oldest fossils on Earth illustrate that it is difficult using all available analytical tools in a laboratory to unambiguously determine if something is truly of biological origin. Recognizing a fossil using the criterion of shape alone poses some challenges, particularly without actually being on the surface of Mars and knowing *a priori* whether it has a fossil record. In contrast, observing movement in extant life is easy. However, not all extant life moves, especially microbes, therefore making it difficult to determine if it is alive by shape alone. Interdisciplinary multi-instrument approaches have been shown to be effective for studies on deep subsurface ecosystems on Earth (e.g., Fisk et al., 2003; Steele et al., 2002; Toporski et al., 2002; Steele).

|  |  |  |  |
| --- | --- | --- | --- |
| **Component** | **% Total Weight (or mass C x10-13 g)** | **Number of Types** | **Preservation** |
| **Water** | 70 (NA) | 1 | Unknown in Organic and mineral phases |
| **Proteins** | 15 | ~2000 | 1000’s without protection by a mineral matrix. ~45Ma with protection?. |
| **Nucleic Acids** |  |  |  |
| DNA | 1 | 2+ | Oldest ? ~350,000 |
| RNA | 6 | (see below) | Days – Months (studies on longevity of RNA other than in clinical settings have not been performed. |
| *rRNA* | 5.5 | 3 | Days – Months |
| *tRNA* | 0.1 | ~32 | Days – Months |
| *mRNA* | 0.3 | 1000’s | Days – Months |
| *Non coding RNA* | 0.1 | 1000’s | Days – Months |
| **Polysaccharides** | ~1 | Uncounted | Chitin - 25Ma. Exopolymer sheaths ~2Ga |
| **Lipids** | 2 | ~50 | Cell wall components - Hopanes 2.7Ga |
| **Amino acids** | 0.4 | ~100 (20 main ones) | As protein diagenesis – Ma.  Chiral signal in fossils lost after ~ 1 Ma. |
| **Sugars** | ~3 | ~200 | Days to weeks (see polysaccharides) |
| **Other small organics** | 0.2 | ~200 | Porphyrins ~ 2 Ga |
| **Inorganic species (C, H, N, O, Fe, P, S etc).** | 1 (~100% dry weight) | ~20 – 30 (including inorganic complexes) | Isotopes may preserved for ? 3.5 Ga for C.  Research is continuing to define other isotope systematics for preservation of a biogenic signature. |
| **Diagenetic Macromolecular material** | Total cell breakdown products (100% dry weight of cells) | Kerrogens (4 types)  Melanoidins (100’s) | Kerrogens – ? 3.5Ga for biogenic (Type 1-3). Type 4 indicative of meteoritic input.  Melanoidins conbination of sugar and proteins, ~50 Ma. |

Generated



Generated



ashing techniques,

Radiation sterilization technologies for whole space craft as well as ‘hot-spot’ removal.

Real time non culture based systems for monitoring amount and types of bioburden.

Providing of a suitable mineralogical bio and organic clean sample blank for proofing critical sample handling pathways and

It should be noted that several of the analytical techniques mentioned in the AFL instrument section cannot undergo heat sterilization. Protocols that either ensure that instruments are delivered cleaned to the level of the space craft and integrated to the craft after heat sterilization, for the use of cooling loops to keep critical instruments cool during sterilization (obviously the previous point would apply here) or alternatives to heat sterilization must be put in place for these technologies to fly.

# 11.0Relationship between AFL and MSL

AFL will depend on the following heritage from MSL.

Precision landing using a novel (non airbag) landing system

The use of RTG technology

The use of remote, contact and analytical suites of instruments

Crude sample processing to be used but improved on AFL

2.AFL will differ from MSL in the following essential respects:

Advanced sample preparation system.

Precision sub-sampling is an advanced sample management step that will allow a scientific focus on meso- to micro-scale discoveries of enhanced astrobiological interest. This will allow a much higher capacity to investigate specific anomalous features.

Liquid extraction. For advanced studies of carbon chemistry, more efficient sample extraction (and instrument delivery) methods are needed.

Better and miniaturized organic molecule and life-detection related instruments.

Greater interplay between

Precision landing, hazard tolerance/avoidance, go-to mobility.

–Will give us the ability to follow-up on specific discoveries, including in “interesting” terrain.

# 12.0The Future of AFL

It is suggested that the SSG reconvene at a later date to

Respond to discovery to hone mission concepts for site selection

Review sample handling and instrumentation choices and feed-forward to a possible sample return mission

Respond to shifting of the AFL timeline from 2013 to 2018, this would include revisiting the instrument choices based on comments from the SSG as to the use of instruments currently in development but of such a low TRL that it could not feature in the 2013 timeframe example include high vacuum and high voltage instrumentation such as electron microscopy, or photoelectron spectroscopy.

In the past, there was competition between in-situ and sample return mission concepts and there was a question as to whether the AFL was to fly before MSR or after. The current schedule envisions an AFL flight as early as 2016 and an MSR some time after 2020.

The advantages of flying in-situ missions first are that they are relatively low cost compared to MSR (although the costly infrastructure put in place for an initial MSR would not be needed for follow up missions) and there are no issues of sample degradation, sample amount, sterilization, quarantine or ‘off nominal’ delivery to earth.

In addition, the strength of in-situ missions is their ability to assess multiple samples over a spatially diverse area without degradation of the samples. AFL will aid in the identification of sample types for future return missions. This may even include aiding sample caching for a future MSR mission, although that would necessitate a further assessment of precision landing of an MSR mission.

A point to remember is that if / once detected life on Mars should be characterized in its entirety for similarity to earth life, evolution and biochemistry (if viable). Therefore both AFL and MSR must be considered necessary tools to be used at the right time to answer science questions within the foreseeable realms of technology..

Several aspects of both the sample handling capabilities for AFL and the choice of instrumentation will allow the further development of robotic tools to explore elsewhere in the solar system e.g. Europa. This instrumentation although initially geared for the detection of life would upon the successful accomplishment of this task be needed to be further developed to characterize that life in whatever form. It will not be enough to ask was/is there life there, the next logical step is how did it arise, how is it different from earth life and why? It is only by taking this step will we able to understand truly the processes of abiotic / prebiotic / biotic chemistry in the solar system.

Note, the bulk of this work and the draft white paper was completed by September 2004. There have been unavoidable delays to its publication. In the meantime thinking about AFL has progressed. This document reflects the thinking in September 2004. Whilst engineering and programmatic changes have occurred since then, the strength of this document lies in the science definition for the mission.

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# 14.0Appendix 1. Discoveries AFL must respond to.

Table 7 Summarizes crucial science discoveries that may also directly affect AFL mission, potential follow up questions and measurements

Generated

# 15.0Appendix 2 - Instrument descriptions and capabilities

In this table, a number of techniques were suggested by AFL SSG members as potentially applicable to one or more identified measurement objectives. This list is not meant to be comprehensive or definitive, but rather to illustrate the kinds of information that would enable instrument development efforts in general to connect to the specific needs of AFL. As such the table does not identify all aspects of each technique, but only those that were discussed in a preliminary analysis of the desired measurements on AFL. The first and second columns identify the technique and the type of measurement(s) with which it is typically associated (Data/Signatures Sought). The third column explicitly lists the most likely AFL measurement requirement that the technique addresses (see Section 7.0). In this way, techniques applicable to a given measurement of interest, or more generally to a mission objective (see Figure 5), can be found by examining those rows containing the category (1-5) desired. This column is meant to serve as an example template, so all potential uses of each technique are not identified. The next three columns indicate the most likely associated tier(s) for the technique, corresponding to the recommended division as discussed above.

The following thirteen columns provide data for *example* implementations of the technique where useful specifications of the sample analyzed and typical instrument parameters could be identified. Given sample data include: 1. the physical form *as acquired or as extracted/analyzed* – solid (s), liquid (l), or gas (g); 2. the type of material from which it is obtained and/or delivered to the instrument; 3. the type of sample preparation required and/or desired (see key); and 4. the typical size or mass of sample, additionally indicating where a technique looks only at the surface of a solid sample rather than the bulk. The first three columns of the Example Technique Characteristics section provide some of the key distances involved: the standoff, the field-of-view (FOV) or spot size, and the scale of the heterogeneity probed, if appropriate. The heterogeneity is indicated by the structures (e.g., layers or grains) that can be individually analyzed with the method’s FOV or spot size. For example, a Hand Lens instrument might look at individual mineral grains and similar size structures within a mm-cm FOV from a standoff focal length of a cm or so. In this example it is the imaging resolution, not the FOV, that determines the smallest structures observable, and that additional data is found in the resolution column. On the other hand, for a laser mass spectrometer, the spot size does roughly determine the spatial resolution of analysis – a spot size below 100 microns could enable analyses of mineral phases on the mm scale; what is then found in the resolution column is in fact the mass resolution, since that is how the term is used for that method. Further, the Mass Range column gives the typical range of molecular weights that are accessible with a given mass spectrometric method.

Finally, the remaining columns provide a correlation of where a technique would be applied in support of various *discovery-responsive measurements* by AFL that would be called for following the discoveries listed in Appendix 2. This separate correlation, beyond the technique-to-measurement requirement-to-mission objective logical chain, permits a greater flexibility and responsiveness of the AFL concept to specific scenarios that may develop from current Mars missions and over the next several years.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 8- Techniques Suggested for AFL by SSG Members** | | | | | | | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | Measurement Tier | | | Example Target/Sample Information | | |  | Example Technique Characteristics (instrument implementation) where appropriate | | | | | | | |  | Discovery/Follow-up per Table 7 | | | |  |  |  |
| Technique | Data/ Signatures Sought | Mmnt Reqts Addessed (Section 7) | Remote Sensing/Standoff | Contact or Close Range | Analytical Lab | Physical Form (Solid, Gas, Liquid) | Example Origin/Host Material | Processing Required/ (Desired) | Sample Mass/ Volume | Distance to Target | Size of Area Probed/ FOV | Target Feature Scale | Selectivity | Detection Limits | Resolution | Precision | Mass Range | Other | Recent Surface Water | Hydrous Mineral Phases | Organic Molecules | Sedimen. Structures | Sedimen. Rocks | Evidence for Fossil Life | Microbes |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| stereo optical imaging | identify targets, evidence of weathering, sedimentation, alteration, etc. | A | x |  |  |  | sedimentary rocks/ structures | n |  | 1m - 10+km | 10cm - 1+km |  |  |  |  |  |  |  | 1 | 6 |  | 1,2,3,4 | 4 | 1,2,3,6,8 | 3 |
|  | identify surface samples | A |  |  |  |  |  |  |  | 10-100 m | 1-10 m | 10cm-1m |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | identify distant sedimentary outcrops | A |  |  |  |  |  |  |  | 1 km | 10-100 m | 1-10 cm |  |  | 10 cm @ 1 km | |  |  |  |  |  |  |  |  |  |
| VIS/NIR Spectroscopy | surface mineralogy, texture | B | x | x |  | s | rocks, fines | n (abr) |  | cm - m |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| mini TES | mineralogy | B | x |  |  | s |  | n (abr) |  | m - km |  |  |  |  |  |  |  |  |  |  |  |  | 1 |  |  |
| long focal length imaging | identify distant sedimentary outcrops | A | x |  |  |  |  | n |  | 10m - km | cm-10m | cm |  |  |  |  |  |  |  |  |  |  |  |  |  |
| laser ranging | distance to target | A | x |  |  |  | boulders, vertical faces | n |  | 100m - km | cm spot |  |  |  | cm @ 100 m | |  |  |  |  |  |  |  |  |  |
| LIBS | elemental composition | B | x |  |  | s | boulders, slopes | n |  | 1 - 25m | mm - cm spot |  | low (l absorb.) | ppmw |  | ~ 10% | elements | laser ablation | | 2,4 |  |  | 2,5 | 3 |  |
| ground penetrating radar | ice, H2O, other | B, C | x |  |  | s | subsurface | n |  | m - 10s m |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |
| seismic sounding | ice, H2O, other | B, C | x | x |  | s | subsurface | n |  | 100's m - km |  |  |  |  |  |  |  |  | 3 |  |  |  |  |  |  |
| neutron spectroscopy | ice, hydrated minerals | B | x | x |  |  | drill cores, fines | n (acq) |  | 10's cm - m's |  |  | high | variable <%-% | |  |  |  |  |  |  |  |  |  |  |
| gamma ray spectroscopy | elemental composition | B | x | x |  |  | any | n |  | 10's cm - m's |  |  | med | variable <%-% | |  |  |  | 5 |  |  |  |  |  |  |
| x-ray spectroscopy | elemental composition | B, E2 |  | x |  |  | any | n (acq) |  | cm | cm+ |  | med | variable <%-% | |  |  |  |  |  |  |  |  |  |  |
| Raman spectroscopy | mineralogy, some geochemical/organic | B, E | x | x |  |  | rocks | n (abr) |  | cm - m | cm+ |  | med |  |  |  |  |  |  | 1,5 | 1,4 |  | 2 | 1 |  |
| micro-Raman spectroscopy | mineralogy, some geochemical/organic | B,D,E |  | x | x |  | rock chips | n (acq, abr) | | mm - cm | < mm |  | med |  |  |  |  |  |  | 1,5 | 1,4 |  | 2 | 1 |  |
| micro-LIBS | elemental composition | B,D |  | x | x | s | rocks, chips | acq,pos |  | mm - cm | < mm |  | low (l absorb.) | |  |  |  |  |  | 2,4 |  |  | 2,5 | 3 |  |
| hand-lens-scale imaging | phase texture/identity | D |  | x |  | s |  | n (abr) |  | cm - m's | 0.1-10 mm | grains |  |  |  |  |  |  |  |  |  |  |  |  |  |
| optical microscopy | fine morphology | D,E |  | x | x | s |  | n (abr) |  | mm - cm | 0.001-1 mm | subgrain |  |  |  |  |  |  |  |  | 2 |  |  | 1,2,3,6,8 |  |
| confocal microscopy |  | D,E |  |  | x | s |  |  |  | mm | 0.001-1 mm | subgrain |  |  |  |  |  |  |  |  | 2 |  |  | 1,2,3,6,8 |  |
| near-field microscopy | very high res imaging | D,E |  |  | x | s | flat chip | acq, pos |  |  |  | subgrain |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Mossbauer | Fe-bearing mineralogy | B |  | x | x | s |  |  |  | mm - cm |  | avg |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Fe-NMR |  | B |  | x |  | s |  |  |  | mm - cm |  |  | high |  |  |  |  |  |  |  |  |  |  |  |  |
| XRD/XRF | mineralogy | B,D |  |  | x | s | drill cores, fines | acq, pow | mg's | 0 | whole sample | avg or grains | |  |  |  |  |  |  | 1 |  |  | 1,5 |  |  |
| FTIR | mineralogy, some geochemical/organic | B |  |  | x | s |  |  |  |  |  |  |  |  |  |  |  |  |  | 1,5 | 1,4,6 |  | 2,5 | 3 | 4 |
| VCD |  |  |  |  | x | s |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| deep UV fluorescence | organics: identity, oxidation state, … | B,D,E |  | x | x | s |  | n (abr) | surface? | mm - m |  | grain scale+ | |  |  |  |  |  |  |  | 1 |  |  | 3 |  |
| pyrolysis/GCMS | organic and some mineralogical/inorganic composition; isotopes | B,E |  |  | x | s,g,l |  | acq, pos, vac | mg-10's mg | 0 | whole sample | avg | low |  |  |  |  |  | 4 |  | 1,5 |  | 5 |  |  |
| chemical derivatization | less-tractable organics | E |  |  | x | s,l |  | liq |  | 0 | whole sample | avg |  |  |  |  |  |  | 4 |  | 1,4,7 |  | 5 |  |  |
| isotope ratio MS (IRMS) | C and other isotopes for bio-fractionation, age dating | E2 |  |  | x | s,l |  | acq, pos, vac | | 0 | whole sample | avg |  |  |  |  |  |  | 2 |  |  |  |  |  |  |
|  | compound-specific IRMS using sampling selectivity | E2 |  |  |  |  |  |  |  |  | whole sample | avg | cmpd isolated w/pyr, GC,or other proc. | | | |  |  |  |  |  |  |  |  |  |
| chiral GC | enantiomeric excess (ee) | E3 |  |  | x | s,g,l |  | acq, pos, gas | | 0 | whole sample | avg |  |  |  |  |  |  |  |  | 3 |  |  |  |  |
| circular dichroism | enantiomeric excess (ee) | E3 |  |  | x |  |  |  |  | 0 |  | avg |  |  |  |  |  |  |  |  | 3 |  |  |  |  |
| liquid chromatography (LC) | organics, ee | E |  |  | x | s,l |  | liq |  | 0 | whole sample | avg |  |  |  |  |  |  | 4 |  | 1,3,5 |  | 5 |  |  |
| 2D GCMS/TOF-MS | organic and some mineralogical/inorganic composition; isotopes | B,E |  |  | x | s,g,l | rocks/cores, fines | acq, pos, vac | 10's mg | 0 | whole sample | avg | low |  |  |  | ~1E3-1E5+ | | 4 |  | 1,5 |  | 5 |  |  |
| electrospray ionization MS (ESI/IMS/CIT-MS) | | E |  |  | x | s,g,l |  | acq, pos, vac | g's | 0 | whole sample | avg | low |  | Dm/m 1E2-1E3+ | |  | contact w/ fluidized sample | | |  |  |  |  |  |
| laser ablation TOF-MS | local elemental/isotopic composition | B,D |  |  | x | s | rock chips, fines | acq, pos, vac | surface | 0 | 10mm - 1 mm | grain scale+ | low (l absorb.) | ppbw-ppmw | Dm/m 1E2-1E3 | 5-25% | ~ 300 |  | 4 | 2,4 |  |  | 2,5 | 1,3 |  |
| LD/MALDI-TOF MS | high-MW organics; some inorganic molecules | D,E |  |  | x | s | rock chips, fines | acq, pos, vac (pow, liq) | surface/prep film | 0 | 100mm - 1 mm | grain scale+ | med (l absorb.) | fmol-pmol | Dm/m 1E3-1E4 | | ~1E3-1E5+ | |  |  | 1,2,4,7 |  |  | 3 | 4 |
| REMPI-MS/RIMS | organics, elements (trace) | E |  |  | x | s |  | acq, pos, vac | | 0 | 10mm - 1 mm |  | very high (l absorb.) | s. atom - pmol | Dm/m 1E2-1E4 | | ~ 1E3 |  |  |  |  |  |  |  |  |
| AP-MALDI-MS (TOFMS or ITMS) | organic, inorganic molec. | D,E |  | x | x | s | rocks, ices | vac | surface | mm | 10mm - 1 mm | grain scale+ | med (l absorb.) | fmol-nmol | Dm/m 1E3-1E4+ | | ~ 1E3-1E5 |  |  |  |  |  |  |  |  |
| electrospray TOF-MS | high-MW organics | E |  |  | x | s,l | rocks/cores, fines | acq, liq, pos, vac | | 0 | whole sample | avg | med |  | Dm/m 1E2-1E4 | | ~1E4-1E5+ | |  |  | 1,2,7 |  |  | 3 | 4 |
| TOF-SIMS | chemical imaging | B,E |  |  | x | s | rock chips | acq, pos, vac | surface | 0 | 50nm-50mm | sub-grain+ | low |  | Dm/m 1E3-1E4 | | ~1E3-1E4 |  |  |  |  |  |  |  |  |
| ICP-MS | trace elements | B |  |  | x | s,g,l | rock chips, fines | acq, pos, vac, gas | | 0 | whole sample | avg or grains | low | pptw-ppbw | Dm/m 1E3+ | 0.1-10% | ~ 300 |  | 2,4 |  | 1,3,5 |  | 5 |  |  |
| TIMS | isotope ratios (~IRMS) | B,E2 |  |  | x | s |  | acq, pos, vac | | 0 | whole sample | avg | low | pptw-ppbw | Dm/m 1E3+ | 0.1-1% | ~ 300 |  | 2 |  | 5 |  |  |  |  |
| AFM | nanoscale imaging | D, E3 |  |  | x | s | flat chip | acq, pos | chips |  | 1nm-1mm | sub-micron | |  |  |  |  |  |  |  |  |  |  |  |  |
| TEM/SEM | nanoscale imaging | D |  |  | x | s | flat chip | acq, pos, vac | chips |  | 1nm-1mm | sub-micron | |  |  |  |  |  |  |  |  |  |  |  |  |
|  | image microbes in ice cores | D,E3 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| XPS | chemical comp. and bond state | B,C |  |  | x | s,l |  | vac | 100's mg |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Auger spectroscopy | bond state of elements | B,C |  |  |  | s,l |  | vac | 100's mg |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| amino-acid sensors (eg MOD) | detection of amino acids | E |  |  | x | s,l |  | acq | 100's mg |  | whole sample |  | high |  |  |  |  |  |  |  | 1,3 |  |  |  |  |
| oxidant sensors | detection of oxidants | C |  |  | x | s,l |  | Acq, dry | 100's mg |  | whole sample |  | high |  | per sample weight | |  |  |  |  | 6 |  |  |  |  |
| bio-assay chip lab |  | E |  |  | x | s,l |  | liq | 100's mg | 0 | whole sample |  | high | pptw | per sample weight | | Kda |  |  |  | 7 |  |  | 1,5,6 | 1,5,6 |
| micro-array sensors |  | E |  |  | x | s,l |  | Liq | 100's mg |  | whole sample |  | high | pptw | per sample weight | | Kda |  |  |  | 7 |  |  | 1,5,6 | 1,5,6 |
| MORD |  |  |  |  | x | s |  |  | 100's mg | 0 | whole sample |  | high |  | per sample weight | |  |  |  |  |  |  |  |  |  |
| fluorescence staining | organics | E |  | x | x | s,l |  | Liq | 100's mg |  | whole sample | avg | high | single cell | per sample weight | |  |  |  |  | 7 |  |  |  |  |
|  | SYBR gold, SYTO, DAPI nucleic acid stains for counting microbes | E |  |  | x | s,l |  | Liq | 100's mg |  | whole sample |  | Medium | single cell | per sample weight | |  |  |  |  |  |  |  |  | 1.5.6 |
|  | CTC, tetrazolium salt redox stains for individual cells | E |  |  | x | s,l |  | Liq | 100's mg |  | whole sample |  | Medium | Single cell | per sample weight | |  |  |  |  |  |  |  |  | 1,5,6 |
| isotopic labelling | 14CO2 or 3H for total population activity | E |  |  | x | s,g,l |  | Lig | 100's mg |  | whole sample | avg | medium | single cell | per sample weight | |  |  |  |  |  |  |  |  | 1,5,6 |
| flow-cytometry |  | E |  |  | x | s,l |  | liq | 100's mg |  | whole sample | avg | medium | single cell | per sample weight | |  | If have required media | | |  |  |  |  | 1,5,6 |
| culturing/cell-growth assays |  | E |  |  | x | s,l |  | liq | 100's mg |  | whole sample | avg | high | single cell | per sample weight | |  | If have required media | | |  |  |  |  | 1,5,6 |
| ATP and LAL enzyme assays |  | E |  |  | x | s,l |  | liq | 100's mg |  | whole sample | avg | high | pptw | per sample weight | |  |  |  |  |  |  |  |  | 1,5,6 |
| DNA extraction/PCR |  | E |  |  | x | s,l |  | liq | 100's mg |  | whole sample | avg | high | 100 cells | per sample weight | |  | with correct primers | | |  |  |  |  | 5,6 |
| capillary electrophoresis (CE) |  | E |  |  | x | s,l |  |  | 100's mg |  | whole sample | avg | high | pptw | per sample weight | |  |  |  |  | 7 |  |  |  | 1,5,6 |
| microcalorimetry |  |  |  |  | x |  |  |  | 100's mg |  | whole sample | avg | medium | pptw | per sample weight | |  |  |  |  | 7 |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **KEY:** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| n - can be operated with no sample acquisition/processing | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| abr - abrasion to remove surface layers | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| acq - sample acquisition from host matl (via whatever means) | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| pow - powdering of solid sample | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| pos - sample positioning (e.g., manipulation to oven, point of focus or extraction) | | | | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| vac - vacuum processing |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| liq - liquid processing |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| gas - gas processing |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |