**The Astrobiology Field Laboratory**

September 26, 2006

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

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# Membership

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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.

|  |  |
| --- | --- |
| **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. |

|  |  |  |  |
| --- | --- | --- | --- |
| **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. |

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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 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |