Search for life on Mars

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Abstract A multi-user integrated suite of instruments designed to optimize the search for evidence of life on Mars is described. The package includes:
- Surface inspection and surface environment analysis to identify the potential Mars landing sites, to inspect the surface geology and mineralogy, to search for visible surficial microbial macrofossils, to study the surface radiation budget and surface oxidation processes, to search for niches for extant life.
- Subsurface sample acquisition by core drilling
- Analysis of surface and subsurface minerals and organics to characterize the surface mineralogy, to analyse the surface and subsurface oxidants, to analyse the mineralogy of subsurface aliquots, to analyse the organics present in the subsurface aliquots (elemental and molecular composition, isotopes, chirality).
- Macroscopic and microscopic inspection of subsurface aliquots to search for life’s indicators (paleontological, biological, mineralogical) and to characterize the mineralogy of the subsurface aliquots.

The study is led by ESA Manned Spaceflight and Microgravity Directorate.

Introduction

The early histories of Mars and Earth clearly show similarities. Geological observations collected from Martian orbiters suggest that liquid water was once stable on the Mars surface, attesting to the presence of an atmosphere capable of decelerating carbonaceous micrometeorites. Therefore, chemical evolution may have been possible on Mars. The Viking 1 and 2 lander missions were designed to address the question of extant life on Mars. Three experiments were selected to detect metabolic activity such as photosynthesis, nutrition and respiration of potential microbial soil communities. The results were ambiguous since although “positive” results were obtained, no organic carbon was found in the Martian soil by gas chromatography-mass spectrometry. It was concluded that the most plausible explanation for these results was the presence, at the Martian surface, of highly reactive oxidants like H2O2 which would have been photochemically produced in the atmosphere (Hartman and McKay, 1995). The Viking lander could not sample soils below 6cm and therefore the depth of this apparently organic-free and oxidizing layer is unknown. Bullock et al. (1994) have calculated that the depth of diffusion for H2O2 is less than 3 meters. Direct photolytic processes can also be responsible for the dearth of organics at the martian surface (Stoker and Bullock, 1997).

The alpha proton X-ray spectrometer (APXS) on board the rover of the Mars Pathfinder mission measured in 1997 the chemical composition of six soils and five rocks at the Ares Vallis landing site. The analyzed rocks were partially covered by dust or a weathering rind similar in composition to the dust. Some rocks are similar to terrestrial andesites

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but it is not certain that these rocks are igneous. The texture of other rocks are difficult to interpret and might be sedimentary or metamorphic (Rieder et al., 1997).

Although the Viking missions were disappointing in the first instance for exobiology, in the long run the programme has proven extremely beneficial for the investigation of the possibility of life on Mars. Prior to Viking it had been apparent that there was a small group of meteorites, all of igneous origin, called the SNC (after their type specimens Shergotty, Nakhla and Chassigny) that had comparatively young crystallisation ages equal to or less than 1.3Ga (Jagoutz and Waenke, 1986). One of these meteorites, EETA 79001, was found on Antarctica in 1979. It had, trapped within glass pockets, gas which both compositionally and isotopically matched, in all respects, the make up of the martian atmosphere as measured by the mass spectrometer utilised for the assessing the soil for the presents of organic compounds (Bogard and Johnson, 1983; Becker and Pepin, 1984; Carr et al., 1985). The data provide a very strong argument that at least that particular SNC meteorite comes for Mars, thus supporting the circumstantial conclusion that materials of young age must have derived from a planetary-sized body. There are now twelve SNC meteorites known in total; others were found more recently on the Antarctic Ice Cap including one of much older age ALH 84001. They can be all shown to be related by comparing their oxygen isotopic compositions. Only these twelve specimens (out of a total of ca 20,000 meteorites) define a correlation line of slope one half on a plot of $\delta^{18}$O vs $\delta^{13}$C.

The two SNC meteorites EETA79001 (Wright et al., 1989) and ALH84001 (McKay et al., 1996; Grady et al., 1994) supply new and highly interesting information. A subsample of EETA79001 excavated from deep within the meteorite has been subjected to stepped-combustion. The CO$_2$ release from 200°C to 400°C suggests the presence of organic molecules. The carbon is enriched in $^{12}$C with $\delta^{13}$C of about -27‰. The difference between organic matter and carbonates in meteorites is greater than the shift seen on Earth which could also be indicative of biosynthesis but some as yet unknown reason cannot be ruled out. McKay et al. (1996) reported the presence of PAHs, carbonates globules and ovoid features which may represent a signature of relic biogenic activity on Mars. Taken individually, the observations about the carbonates and PAHs can, however, be explained by non-biological means. For instance, there are conflicting values for the formation temperature of the carbonates: major-element chemistry implies a temperature of more than 500°C (Harvey and McSween, 1996) incompatible with bacterial life, whereas oxygen isotope composition gives less than 100°C. PAHs are not synthesized in any biological system but are produced by metamorphism of marine plankton and early plant life. Their presence in the unmetamorphized ALH84001 cannot therefore be taken as a convincing biomarker. No analysis of the composition of the ovoid feature edges has been performed to show wether they contain carbon or not. The carbonates that contain the microfossils are found in igneous rock rather than in a sediment (Grady et al., 1996).

Even if the evidence for ancient life in ALH84001 is not conclusive, the two Martian meteorites show the presence of organic molecules suggesting that organic matter required for the emergence of a primitive life may have been present on the surface of Mars. Therefore, microorganisms may have developed on Mars until liquid water disappeared. Since Mars probably had no plate tectonics and since liquid water seems to have disappeared from Mars surface very early, the Martian subsurface perhaps keeps a frozen record of the very early forms of a terrestrial-like life.

**ESA Exobiology Science Team**

ESA Manned Spaceflight and Microgravity Directorate directed and supported an Exobiology Science Team requested to carry out a study of the experimental strategy and the instrumentation necessary to search for indicators of life, especially extinct life, on or within the surface of Mars. Included in that would be a search for organic and prebiotic organic compounds. It was assumed that such a search would be carried out using a Mars Lander and a small Rover vehicle. The Lander is considered as the centre for subsurface sampling and for the in situ sample preparation and analysis processes. The Rover then provides a selection of rock samples from nearby locations either as small core samples or as small (cms) rocks, for analysis in the Lander.

The Team composed of European experts in radiation biology, planetary geology, geochemistry, mineralogy, and meteorology, as well as exobiology, since each of these science areas has considerable relevance in any attempt to search for life elsewhere and to study its origins.

The Team adopted the following objectives:

- to carefully select a set of landing sites having environments of high exobiology potential to increase the chances of detecting biosignatures, whether chemical or morphological.
- to carefully inspect the gross features of the landing site surface.
- to provide for sampling of that environment from a range of locations and from positions where the effects of surface oxidation processes should be reduced (subsurface drilling).
- to subject those samples to an integrated set of measurements which, taken together, reduce the chances of ambiguity in the interpretation of potential biosignatures.

**Site selection**

The following sites were selected on the basis of a high potential exobiology significance, on currently available information, with some constraints on latitude and size. The lack of mineralogical mapping still limits the site selection process. The results from future detailed orbital
surveys may therefore lead to a change in this list:

-Marca Crater: lake beds, several craters with lacustrine deposits
-Hydroates Chaos: lacustrine deposits, complex basins with rock debris
-Apollinaris Patera: hydrothermal systems, volcano with rock debris of various ages
-Elysium Plain: lacustrine deposits, but may be covered by extensive lava flow
-Gusev Crater: lake beds, lacustrine basin with large outflow channel
-Capri Chasma: probable waterlain deposits, chaotic terrain / sediments

**Macroscopic surface inspection**

Surface inspection would have two main functions. It would seek evidence of gross features in surface rock structures which may indicate previous biological activity, at its most simple that could be the equivalent of degraded stromatolite structures. It would also be used to identify target rocks for subsequent close-up examination and for possible interior rock sampling. The equipment to perform these functions will likely be derived from that currently selected for flight on future Mars missions.

**Sample acquisition**

Oxidation effects at the surface are assumed to be responsible for the negative results so far in the search for organics. Both direct photochemical and chemical processes have been shown theoretically to be likely, with hydrogen peroxide as a major chemical agent. As yet no in situ measurements have been carried out and this remains as one of the goals of this experiment system. The influence of the oxidation process is expected to be limited in sedimentary rocks to the first few centimetres below the weathered outer 'rind', although no studies are as yet available to confirm this. The Team recommended to focus on this particular problem. Subsurface sampling by core drilling into consolidated sediments and performing analysis of sequentially presented samples will provide the essential information on the variation of oxidation state with depth. That will be in addition to a morphological, elemental, isotopic, mineralogical, and molecular analysis of the samples, as described below. Site selection is intended to increase the chances of the Lander being finally located in a region which has relatively low concentrations of aeolian dust mounds and a high probability of underlying dense sedimentary material.

Sample Acquisition is principally by core drilling and sequential core sample extraction. The main drill is for subsurface sampling, with a core diameter <1 cm. Sampling depth is at least 1 m. Due to its size, and other factors, this large drill will have to be located on the main Lander. The maximum drilling depth achievable will depend on the constraints imposed by the Lander configuration on the accommodation of the multiple drill bits, as well as other resource limitations and the nature of the regolith. The actual mounting of the drill on the Lander should if possible include the possibility to adjust the position of drill entry over a limited range.

Sampling of the unoxidised interior of large surface rocks below the weathered rind is to be accomplished by a core drill penetrating up to 15 cm. This drill would be mounted on the Rover, together with the necessary sample storage containers. The core diameter would match that of the main subsurface drill. It is envisaged that the primary purpose of the Rover will be to obtain selected samples for in situ detailed analysis at the Lander and, on the basis of those analyses, for a subset to be stored for return to Earth. This subset would be in addition to selected subsurface samples. Sample acquisition from several centimetres depth may follow after an initial examination below the surface rind of the rock. A surface grinder and microscope is planned for that initial task. An alternative approach to rock sampling was also considered. This involved simply the collection of small (cms) sized surface 'rocks' by the Rover and their subsequent sectioning at the Lander, preparatory to microscopic analysis. This avoids the complications of the Rover based drilling operations, although at the cost of some biasing in the sampling process.

**Sample inspection and analysis**

First, the samples are observed macroscopically after suitable preparatory treatment. This basic mineralogical inspection is an essential first step. It characterizes the sample and allows the possibility of observing any embedded larger fossil structures. Carefully selected samples may then be passed for spectroscopic and chemical analysis. Where there are indications of possible smaller scale fossil structures those samples can be subjected to submicron scale morphological analysis.

**Sample inspection**

On Earth, the earliest prokaryotic microbial ecosystems have left two main categories of morphological fossil evidence. At the macroscopic level are the laminated biosedimentary structures (stromatolites) which have been left by mat forming bacteria. These microboliite structures have a record extending back some 3.5 Ga on Earth. If Mars had a comparable early period of abundant water, then it is possible that macroscopic microboliite structures may be associated with the oldest of the Martian sedimentary structures. Hence, degraded macroscopic structures of similar origin might be observed in sedimentary surface rocks and scarp by a panoramic camera with a resolution of about one millimetre. The camera will also be extensively used in a geological and mineralogical context. The second main category of morphological fossil evidence left on Earth derives from the cellular relics of individual micro-organisms. These microfossils, whose record also extends back to about 3.5 Ga, are to be found ranging in size from <5 microns for some individual bacteria through to about 1 mm for filamentous cyanobacteria. Consequently, by analogy, low
power and high power optical microscopes will be required, together with an atomic force microscope to reach the submicron resolution level.

**Sample analysis**

The resulting mineralogical and geochemical analyses, together with the petrological studies using the observational instruments, provide the essential basic information on the general planetological setting of the site, the local environment, and on any traces of past or present biological activity.

The mineralogical characterization of the site samples will comprise of the following objectives:

- mineralogy and sedimentology of the soil, and wind/water deposited sediments, regolith and grain size/shapes secondary minerals such as clays, carbonates, zeolites, hydrates, chlorites.
- mineralogy of mobile phases and hard ground cements (halogenides, sulphates, nitrates, silica, carbonates, iron oxhydroxides).
- mineralogy, texture and bulk chemistry of primary rocks.
- search for biomarkers (framboidal sulphides or oxides, bio-phosphates, manganese oxides, oxalates, silica, biogenic magnetite, barite, and the fossil structures).
- the quantitative determination of water, particularly as a function of depth.
- the depth profile of the abundance of oxidants in the consolidated sediments.

Geochanical analysis of these same samples will establish their elemental bulk composition. Major, minor and trace element abundances will help define the geological history of the site and an analysis of the oxidation state of certain elements (e.g., Fe, Mn, S, N, ) will provide information on the redox conditions there and their historical development. A knowledge of the relative abundances of the biologically significant elements C, H, N, O, S and P, and their distribution between organic and inorganic matter is of particular interest. The abundance of nitrogen and its oxidation state in the Martian soil will be of significance in determining what happened to the initial atmospheric nitrogen.

As yet no organics have been found on Mars and their discovery and analysis would be of prime importance for exobiology. It will be necessary however to carefully differentiate between organics of an abiotic origin, especially those of meteoritic origin. On Earth, the primary biopolymers undergo a complex process of degradation and condensation following the death of the organism. The result is a complex and chemically stable macromolecular material (kerogen). In addition, certain stable lipid rich biopolymers survive this degradation process, to contribute directly to the constitution of the kerogen. Sediments may also contain stable organic compounds, especially metalloporphyrin pigments, which have survived at least in part, the processes of alteration. Many can be classified as biomarkers on the basis of their structure and/or carbon isotopic composition. Such biomarkers and kerogen of recognisable biological origin have been found in sediments on Earth which date back at least 0.5 Ga. It is therefore conceivable that such materials might be detected on Mars, given appropriate sites. Taking into account factors such as survivability, especially in an oxidising environment, has led to the following priority order in searching for organics:

- Volatile low molecular weight compounds, including hydrocarbons (especially methane), alkanoids acids and peroxy acids
- Medium molecular weight compounds, including hydrocarbons (straight and branched chain, isoprenoids, terpenoids, steroids, and aromatics).
- Macromolecular components, which would be kerogen-like components, oligo- and polypeptides.

Isotope ratios can provide a very valuable set of chemical biomarkers. Most notable is the $^{13}$C depletion in favour of $^{12}$C in photosynthesis. On Earth, this depletion amounts to 20 to 30% in the average biomass when compared to that in inorganic carbon and this difference has been maintained over about 3.5 Ga. Similarly, substantial isotopic fractionation, as much as 30%, in favour of hydrogen against deuterium is found to occur through the activity of methanogenic micro-organisms on Earth. In addition a determination of $^{15}$N/$^{14}$N can provide important information on possible biological activity, as can the $^{34}$S/$^{32}$S isotopic composition change between sulphides and sulphates.

**Integrated instrument package**

Sample preparation for microscopy and spectroscopy requires the conversion of a core into a smooth surface. A hard rock sectioning system was proposed for the cutting/smoothing process. The chemical analysis requires access to grains. A basic grinding system is therefore an integral part of the sample preparation system. Precautions obviously are needed to deal with contamination.

Observational methods selected involve a macroscopic system, low and high resolution optical microscopes, and an atomic force microscope to reach the nanometre resolution level.

Analytical methods include radiation and particle spectroscopic techniques, together with mass discrimination instruments. Each of these may be applied to the samples derived from surface rocks and from the subsurface drilling. The following instruments have been identified as suitable, in total, to cover the range of determinations, elemental, isotopic, and molecular, outlined above:

- Alpha/Proton/X-Ray Spectrometer for elemental analysis for all elements except H and He
- Mössbauer spectrometer for Fe-bearing minerals and Fe-oxidation state and ratios.
- Laser Raman Spectrometer 200 - 3500 cm$^{-1}$ and 8
cm<sup>-1</sup> resolution for molecular analysis of organics and of minerals. Pyrolytic Gas Chromatograph and Mass Spectrometer for inorganic/organic compound analysis, isotopic ratio and chirality determination.

The Lander integrated instrument package (including the drill) levels at 26kg whereas the Rover intrumentation represents a 7kg payload.

Mission opportunities

ESA will launch Mars Express in June 2003. The orbiter will include instruments to study the surface mineralogy and the atmosphere. The launch capability permits a 60kg lander to run exobiology studies of the subsurface. A lander named Beagle 2 (to commemorate the second surveying of the original Beagle which provided Charles Darwin with the information for his Earth shattering Evolutionary theories) has been designed by a European consortium led by Colin Pillinger. The instrument payload is constrained to 6.5kg. Two identical panoramic stereoscopic cameras will give a complete panoramic coverage of 360° in azimuth and 90° in elevation. Sample preparation and acquisition will be achieved with a rock grinder/corer on a robotic arm for rock surface grinding and coring and with a self-burying penetrator (mole) for subsurface sampling. The grated rock surfaces will be examined by a microscope, a Mössbauer spectrometer and an APX spectrometer limited to the X-ray spectrum. The X-ray spectrometer will give the potassium content for age dating and the major elements Mg, Al, Si, S, Ca, Ti, Cr, Mn and Fe for rock type identification. Organic molecules and isotopes will be analyzed by gas chromatography - mass spectrometry after oxydative pyrolysis.

Beagle 2 will constitute a first steep in the Mars exobiology exploration. The second step could be conducted in 2005 in complement to NASA Mars Sample Return mission planned to collect Martian samples to be brought back to Earth for analysis in 2008. Drilling into Martian consolidated sediments and in situ analysis of the cores will be a complementary way to explore the biological past of Mars and to search for organic remnants of meteoritic and cometary bombardment. The complete integrated package designed by the ESA Mars Exobiology team would fulfill such an objective.

References


