Science Rationale and Priorities for Subsurface Drilling in ’07

Final Report

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Organizational Outline

Appendix III: Related MEPAG Goals, Objectives and Measurements (prepared by Greg Wilson, Diana Blaney, and Sylvia Miller).

Appendix IV: Terrestrial Well Logging Techniques & Instrumentation (PPT presentation prepared by Quinn Passey)

Appendix V: Italian Participation in the Mars Exploration Program: The *Deedri* Shallow Drill and *IPSE* Science Payload.

I. Executive Summary

Conclusions

We have reached the following conclusions regarding the science rationale and priorities for subsurface drilling as part of the proposed 2007 Mars mission. Given constraints communicated to us by the 2007 pre-project team, we have not considered depths greater than 200 m.

1. *Depth of Penetration:* For overall science value, the greater the depth of penetration, the better. However, the science value does not increase uniformly with depth of access. The depth needed to have a reasonable chance of answering high priority science questions is listed below.
   - 1-2 m. Soil/regolith petrology, regolith physical properties, atmosphere/regolith interactions on diurnal to seasonal timescales, and natural seismicity.
   - 5 m. Heat flow, soil/regolith stratigraphy, and long-term (multiyear) volatile transport.
   - 10 m. Likely penetration below the surface oxidized layer (enabling a reasonably definitive test for organics and other biomarkers), and improved access to near-surface stratigraphy.
   - 20 m. Potential access to ice-saturated frozen ground (depending on the latitude and local properties of the landing site), reasonable chance to sample bedrock (basic petrology and geology studies), improved seismic coupling and heat flow measurement.
   - >20 m. Probability of access to bedrock increases with greater depth. Accessing the source stratigraphy of the gullies, and possible near-surface liquid water, will require a hole with a depth of at least several hundred meters. Under current climatic conditions, and outside of local geothermal anomalies, access to liquid water appears unlikely for depths shallower than several kilometers. However, massive lenses of segregated ground ice (representing the frozen discharge of the outflow channels or a relic of an early ocean), are another high-priority volatile target that may be present at depths as shallow as several tens of meters.

2. *Importance of Multiple Holes:* For most of the subsurface science issues identified by MEPAG, the potential return from a single deep hole is considered more valuable than from multiple shallow holes. However, if other factors constrain the maximum drilling depth to <5 m, then the capability to drill multiple (~3-5) holes becomes more desirable -- adding significant confidence to the characterization of local near-surface properties.

3. *Value of Mobility:* For drilling missions to depths 3 10 m, a limited degree of mobility (i.e., from ~1 to several 10s of meters) would be useful (but not mandatory) to optimize the specific place where drilling will begin. Greater mobility would be desirable if the maximum drilling depth is shallow (< 5 m), to insure that the measured properties are representative of the targeted area. Mobility of as much as several kilometers would be necessary if the desired subsurface target occupied only a small fraction of the mission's landing ellipse.

4. *Value of Retrieving a Sample for Surface Analysis:* Some kinds of investigations will require that samples be delivered to the surface for analysis, while others will require measurements that can only be made in-situ in a borehole. In some instances, investigations could be conducted by either approach. For most life-related investigations, sample retrieval is necessary given the current state of technology.

However, down-hole analysis is preferable for assessing volatile saturation and state, and this mode is mandatory for recording heat flow and seismic data. Most geologic questions (composition, lithology, porosity) can be answered in either mode. We conclude that a reasonably complete drill-related science package will need to include a mix of these capabilities.

Recommendations

1. We recommend that every effort be made to achieve a minimum penetration depth of 20 meters in 2007. If resource (mass, power, time) constraints make this impossible, the target penetration depth could be reduced to 10 meters with some sacrifice of science return, and to 5 meters with significant sacrifice. Some of the science questions that require a penetration depth of 5-10 m (especially organic geochemistry and thermal characteristics) are important to designing the sample acquisition strategy for MSR in 2011.

2. We also recommend that, because most of NASA's space-qualified instruments are presently configured for surface, rather than subsurface, usage, a greater emphasis should be placed on the development of both down-hole instruments and sample acquisition technology.

II. Introduction: Task of the '07 Drilling Science Subgroup.

In December 2000, at the request of the Mars Program Office, a team was formed (under the direction of Dave Beaty) to assess the feasibility of including a drill in the payload of the proposed '07 Lander. The team was broken into two subgroups -- one to examine the engineering issues associated with drilling (to depths ranging from 0-150 m) and another to consider the scientific motivation and potential return from such an effort.

The principal task of the science subgroup was to address the following questions:

1. Science. What is the science justification for drilling in '07? This justification will need to be linked to the MEPAG planning document. Specific questions include:
   a. What is the dependency of science justification with penetration depth?
   b. How much of the science is dependent on the delivery of samples from the subsurface to an analytic station at the martian surface?
   c. For science related to sample collection and delivery to the surface, how sensitive are the science goals to the sample particle size and to the accuracy of knowledge of the collection depth?
   d. Which instruments will need to be associated with a drilling operation to achieve a range of possible science returns?
   e. Are there additional HEDS (or any other) justifications for drilling in '07?
2. Instruments. What are the possibilities for instruments that could be ready within approximately the next two years? Assume that instruments may be needed for both sample analysis at the surface, and downhole application. What are estimated mass and power requirements of these instruments? What is the present TRL level of these instruments?
3. Mobility. Is there incremental scientific or engineering value in drilling from a mobile platform as compared to drilling from a fixed platform? Is the incremental value sufficient to justify any increased risk or cost?

This report is our response to these issues.

III. Science Justification for Drilling.

Drilling investigations of the Martian subsurface are motivated by a number of scientific and engineering interests associated with the geologic, hydrologic, and climatic history of the planet; the search for life; and the identification of potential hazards and resources for future robotic and human exploration. These investigations address the following principal goals:

- To understand the distribution and state of subsurface water and other volatiles.
- To understand the geology and evolution of the upper crust and regolith (including lithology, composition, physical properties and structure).
- To determine the nature and distribution of oxidants as function of depth.

- To search for organic molecules and other potential indicators of past or present life.
- To characterize the geophysical environment, including heat-flow, seismicity, stress & strain, and associated geophysical properties.

A prioritized list of investigations and measurements, related to the above goals, is presented in Appendix I – including citations that establish their tracibility to the original MEPAG science document (whose goals are stated explicitly in Appendix III). Appendix II provides a summary of potential instruments, their technical readiness level, and their viability for use on the surface vs. downhole.

A. The Distribution and State of Subsurface Volatiles.

A primary goal of Mars exploration is to determine the 3-dimensional distribution and state of water (and other volatiles) in the subsurface. Within the plausible range of depths that an '07 drill might reach (~1 - 150 m), there are a variety of potential volatile targets, and related measurements, that are important to understanding the diurnal and seasonal exchange between the atmosphere and near-surface regolith, the nature of the past and present climate, the geologic and hydrologic evolution of the planet, the search for life, and the potential presence of hazards and in-situ resources relevant to future human explorers. These potential volatile targets and measurements are discussed in greater detail below.

1. Adsorbed and Chemically Bound Volatiles.

Laboratory experiments have demonstrated that at the temperatures and pressures characteristic of the Martian surface environment, significant quantities of H_2O and CO_2 can be adsorbed by the regolith on mineral grain surfaces (Fanale et al., 1982). Because the amount of H_2O and CO_2 adsorbed per unit specific surface area is strongly dependent on temperature, adsorption is thought to play an important role in "buffering" the diurnal and seasonal exchange of these gasses between the Martian atmosphere and subsurface, especially within the top several meters of the regolith.

A significant amount of H_2O, CO_2, and other volatiles, may also be chemically bound in rocks and regolith (as distinct from gas, liquid or solid phases that may exist within crustal pores). In the case of primary igneous rocks, the content of bound volatiles provides evidence of the bulk water content of the planet and the relationship of igneous activity to the generation of Mars' atmosphere. However, there are likely to be a substantial amount of volatiles locked up in secondary minerals, including chemical weathering products and evaporite deposits, that represents H_2O and CO_2 that was formerly present in the atmosphere and hydrosphere, but that is now tied up as hydrous minerals, carbonates and other chemically-bound crustal sinks.

It is possible that in-situ measurements of total hydrogen abundance, using neutron spectroscopy, could be made in the shallow subsurface to measure the total abundance, distribution and temporal variation of

adsorbed H_2O. However, mineralogical and differential thermal analysis will be required to identify and measure the amount of H_2O, CO_2, and other volatiles chemically bound within crustal rocks and regolith.

Science questions related to this target:

- How much H_2O and CO_2 is adsorbed in the regolith and how does it vary as a function of depth and time on both diurnal and seasonal timescales?
- What is the nature, abundance and distribution of volatile-bearing mineralogy in crustal rocks and regolith?

2. Liquid Water.

Liquid water may be present in the subsurface in a variety of forms and potential distributions. During the summer, at low-latitudes, the temperature of the top few centimeters of the regolith may exceed 273 K for as much as a few hours a day – sufficient to melt near-surface ice or frost and produce transient films of liquid water on mineral grains. The presence of potent freezing-point depressing salts could conceivably extend the duration and extent of melting, particularly at equatorial latitudes. Near-surface liquid water might also occur in association with local geothermal anomalies.

There is a substantial amount of geomorphic evidence that suggests that liquid water was once abundant on the Martian surface (Carr 1996). However, current thermal models suggest that, if any major reservoir of liquid water survives on the planet today, it is restricted to depths of several kilometers or more beneath the surface (Clifford 1993). This belief has recently been challenged by Malin and Edgett (2000), who have identified features in high-resolution MOC images that they interpret as having originated from recent (active within last ~10^7 years, and possibly even today) episodic discharges of near-surface (~100 - 500 m-deep) liquid water. Although extremely rare (being present in less than 1% of all MOC images taken to date), these gullies are found on exposed scarps in both the northern and southern hemispheres within the latitude band of 30° - 70° -- preferentially occurring (by a factor of 2-to-1) on poleward-facing slopes. While the true nature and age of the Malin and Edgett gullies continue to be topics of intense debate, the potential implications of a fluvial origin make them a logical target for shallow drilling investigations.

Science questions related to this target:

- Do near-surface reservoirs of liquid water/brine exist?
- If so, what is their origin, composition, vertical distribution and probable lifetime?
- What geochemical, and potential biological, processes do they support?

3. Massive Bodies of Segregated Ground Ice.

Subsurface water may also be present as massive segregated deposits of ground ice in the northern plains – an expectation based on the possible former existence of a Noachian ocean, and the geomorphic evidence for extensive and repeated flooding by Hesperian-age outflow channel activity. As a result, the volatile stratigraphy of the northern plains is likely to be quite complex, having been built up through multiple

episodes of flooding, freezing, sublimation, and burial. This complexity has undoubtedly been compounded by local differences in hydraulic and geologic evolution arising from impacts, volcanism, tectonism, and other processes, as well as by extreme climatic fluctuations associated with the chaotic evolution of the planet's obliquity (Touma and Widom 1993, Laskar and Robutel 1993, Jakosky et al. 1995). While the resulting fine-scale structure of the crust is expected to exhibit considerable heterogeneity, in many areas the bulk properties of the uppermost ~0.1 – 1.0 km are likely to be dominated by multiple, overlapping deposits of water ice – with individual flows ranging from meters to many hundreds of meters thick. If so, such deposits would provide an ideal (and highly accessible) environment for the preservation of evidence of past life and would also serve as an invaluable *in-situ* resource to sustain future human explorers.

Science questions related to this target:

- Is there evidence of massive bodies of segregated ground ice, resulting from the ponded discharge of the outflow channels or the presence of an ancient ocean, in the northern plains?
- If so, what is the depth/distribution of these ice bodies?
- Do they preserve any evidence of a past climate? Or of subpermafrost aqueous geochemical or biological processes?

4. Saturated/Unsaturated Frozen Ground.

At the Martian surface, the low relative humidity of the atmosphere means that ground ice is generally unstable at latitudes equatorward of ~40° – leading to its progressive sublimation at a rate that is dependent on the mean annual surface temperature, as well as the local thermal and diffusive properties of the crust. Depending on the nature of these properties, their variation with depth, and the potential for replenishment from any deeper reservoir of subpermafrost groundwater, the local depth of desiccation at low-latitudes may range from centimeters to as much as a kilometer -- with the potential for significant and complex variations in saturation state beneath the sublimation front (Clifford, 1998).

The extent of low-latitude desiccation is of considerable interest for a variety of reasons. For example, the presence of ice in the pore space of the regolith can act as a diffusive barrier to the infiltration of oxidants that could affect the preservation of any organic material present in the soil. Knowledge of the presence of ice-rich fine-grained materials in the near-surface is also import to planning future human exploration activities, both as a potential in-situ resource of H_2O and as a civil engineering hazard (i.e., thermal disturbances caused by the presence of large spacecraft or human habitation modules could result in frost heave and related processes that could affect the stability and bearing strength of the regolith).

Science questions related to this target:

- How does the depth of desiccation vary geographically? And how does the saturation state of the crust vary beneath the sublimation front?
- How large is the variability of both of the above at m- to km- size scales?
- Are fine-grained materials (micron-size or smaller) present in sufficient abundance that frost heave of ice-rich regolith is likely to be a major constraint on future robotic or human exploration?

5. Gas Hydrates.

Exotic physical compounds of water ice and various gases, known as gas hydrates, may also be present in the Martian subsurface. Hydrates are formed when hydrocarbons, and other gases (like CO_2 and H_2S), are concentrated under condition of high pressure and low temperature in the presence of H_2O – where they can become stabilized by Van der Waals bonding within the cubic crystalline lattice of water ice molecules.

On Mars, methane may have been produced by biotic (Farmer, 1996; Fisk and Giovannoni, 1999; Max and Clifford 2000) and/or abiotic (Wallendahl and Treiman, 1999) processes. As the internal heat flow of the planet has declined with time, the resulting downward propagation of the freezing-front at the base of the cryosphere would have incorporated any subsurface methane as hydrate -- in concentrations ranging from a dispersed contaminant, to massive deposits (Max and Clifford, 2000).

Under ambient Martian conditions, methane hydrate is stable close to, but not at, the surface. For example, at 200 K, hydrate is stable where the local confining pressure exceeds 140 kPa, which corresponds to a depth of ~15 m (assuming an ice-saturated permafrost density of 2.5×10^3 kg m^{-3}). Given a reasonable estimate of planetary heat flow and the thermal properties of the crust, the base of the hydrate stability zone is expected to extend to depths that lie from several hundred meters to as much as a kilometer below the base of the cryosphere (or roughly ~3-5 km at the equator, to ~8-13 km at the poles).

If a deep microbial biosphere did establish itself on early Mars, then evidence of its presence, in the form of methane hydrate or gas, could well be detectable in the shallow subsurface (Max and Clifford, 2000). The discovery of substantial deposits of methane hydrate, whatever its origin, could also represent an invaluable resource to future human explorers -- providing an important in-situ source of energy and potential feedstock for the production of more complex hydrocarbons and other organic molecules (Ash et al., 1978; Meyer and McKay, 1996).

Several workers (e.g., Miller and Smythe, 1970; Milton, 1974; Kamatsu et al. 2000; Kargel et al. 2000) have argued that substantial amounts of CO_2 hydrate might also be present in the Martian subsurface. The molecular structure of CO_2 hydrate is essentially identical to methane hydrate, with the exception that CO_2 substitutes for CH_4 as the guest molecule in the crystalline lattice of water ice (Miller and Smythe, 1970; Sloan, 1997). The stability field of CO_2 hydrate is also similar, but shifted to slightly shallower depths – extending from ~5 m (corresponding to a confining pressure of ~50 kPa) at 200 K to a maximum depth defined by the location of the 283 K isotherm. The most probable mechanism by which such deposits could have formed is by the progressive cooling and freezing of CO_2-saturated groundwater.

Science questions related to this target:

- Are gas hydrates or reduced gasses present in the near-surface?
- If so, what is their distribution and probable mode of origin?

6. Polar Layered Deposits.

As the planet's principal cold-traps, the Martian polar regions have accumulated extensive mantles of layered ice and dust deposits that cover individual areas of ~10^6 km^2 and total as much as 3-4 km thick. From the scarcity of super-posed craters on their surface, these layered deposits are thought to be comparatively young – preserving a record of the seasonal and climatic cycling of atmospheric CO_2, H_2O, and dust, over the last ~10^5 - 10^8 years. For this reason, the polar deposits may serve as a Rosetta Stone for understanding the geologic and climatic history of the planet – preserving a record of variations in insolation (due to quasiperiodic oscillations in the planet's obliquity and orbital elements), volatile mass balance, atmospheric composition, dust storm activity, volcanic eruptions, large impacts, catastrophic floods, solar luminosity, supernovae, and perhaps even a record of microbial life (Clifford et al., 2000).

Unraveling this complex history would be greatly aided by the inclusion of a drill on any future polar mission. A drill would offer the ability to: directly sample the stratigraphic record of seasonal and climate change preserved at the poles; investigate the compositional, rheologic, and thermophysical properties of the polar ice; search for evidence of life; and provide valuable data on the physical and dielectric properties of the layered deposits to assist in the interpretation of orbital radar sounding investigations like MARSIS.

Science questions related to this target:

- What is the composition, structure and chronology expressed in the polar stratigraphy?
- What are the thermal properties and thermal structure of the layered deposits?
- How has the annual mass balance varied with time?
- Is there evidence of internal deformation indicative of glacial flow?

B. Geology, Evolution and Physical Properties of the Near-Surface Crust and Regolith.

A goal of the Mars exploration program is to understand the geologic evolution of the planet's crust -- determining the nature and sequence of the various geologic processes, such as: volcanic, impact and tectonic activity; fluvial and eolian sedimentation; as well as other forms of physical and chemical alteration. Drilling into the near-surface crust will provide an opportunity to assess variations in composition, texture, stratification, unconformities, etc. that will help define its lithology and structure, and provide important clues regarding its origin and subsequent evolution.

1. Lithology.

The nature and magnitude of sedimentary processes through time is of particular interest because fluvial and lacustrine sediments are among the best lithologies to search for evidence of past life and because they record the history and intensity of water processes. Similarly, the stratigraphy and nature of igneous rocks tell us about the volcanic and thermal history of Mars which, in turn, provides insights into the mechanisms and rates at which water and gasses where released to the atmosphere. Finally, the identification and evaluation of former impact and volcanic sites for evidence of past hydrothermal activity has implications for the origin, evolution and fossilized preservation of past life, as well as the mineralogic and volatile evolution of the crust.

Mineralogical and chemical compositions, texture, and primary structure are (as detailed below) important parameters to characterize for identifying igneous, metamorphic and sedimentary rocks. These parameters are best characterized in context by drilling into Mars, particularly if the capability exists to reach depths greater than the local thickness of the eolian mantle or unconsolidated regolith (generally thought to be <5-10 m).

2. Composition.

The composition of the Martian crust (elemental, chemical and mineralogical) is the single most important parameter that can be measured as a function of depth. The composition of the regolith and crustal rocks provides important information about the geologic evolution of the near-surface crust, the evolution of the atmosphere and climate, the existence of past or present life, and the presence of potential resources and hazardous materials for both HEDS and advanced robotic missions.

Although orbiter and lander investigations have provide information about the elemental and chemical composition of the surface, little is known about its mineralogy or about the compositional variability of the subsurface. Drilling will provide the opportunity to assess these characteristics in context and as a function of depth.

To date, nearly all of the instruments that have been developed to make compositional measurements have been designed to function at the surface, onboard a lander or a rover (see Appendix II). While bringing drill cores or cuttings to the surface for analysis is one option, it would be highly desirable to develop the capability to conduct downhole measurements so that samples could be analyzed *in situ* – improving our understanding of their geologic context and minimizing the potential complications associated with both sample retrieval and re-insertion of the drill. Nonetheless, given the present state of technology, some investigations may only be possible by returning samples to instruments located on the surface.

The depth of drilling will depend on the scientific objectives, e.g., 3-5 m may be sufficient for examining the consequences of present-day atmosphere-surface interactions, regolith development, and HEDS-related investigations (a depth that roughly corresponds to the estimated thickness of unconsolidated regolith and that reached by the propagation of the seasonal thermal wave); ~10-25 m for determining atmospheric interactions and regolith development over the past ~10^7 years; and possibly >1 km for understanding the mineralogical record of climatic evolution and crustal development on a timescale of ~10^9 years.

3. Physical Properties.

Among the physical properties that are of interest as a function of depth are: porosity, density, pore- and grain-size distribution, specific surface area, cohesion/aggregation, and permeability (with respect to both gases and liquids). These properties are in addition to the thermal and electromagnetic properties identified in Section III.E.

Knowledge of these properties is particularly important to understanding the volatile response of the regolith and near-surface crust to diurnal (top ~25 cm), seasonal (top 2-3 m), and climatic (top several 100 m)

fluctuations in surface temperature and atmospheric pressure; the distribution and transport of atmospherically-derived oxidants (Section III.C); the susceptibility of the surface to erosion and mass wasting; the geophysical characteristics of the subsurface to active and passive sounding investigations; and to the design of mobility systems, advanced drilling and excavation tools, and – eventually -- foundations and roadbeds associated with future human missions.

4. Age.

The relative age of units accessed by drilling is readily established by their stratigraphic succession. The detailed characterization of these units may also allow them to be recognized elsewhere, where their occurrence may provide clues and temporal benchmarks for assessing the local and regional geologic record.

Absolute ages are required to characterize the times at which formative processes were active. In general, igneous rocks provide the best samples for age determinations; however, other techniques are currently being investigated that may make it possible to obtain absolute ages of depositional emplacement for sedimentary and evaporitic deposits as well. Although the highest degree of accuracy will likely require the return of samples to Earth, a variety of techniques show promise for in-situ application (Doran et al., 2000).

5. Structure.

Drilling will also allow the characterization of the large-scale vertical structure of the crust, including its stratification; the presence of unconformities; the occurrence of folds, faults, jointing, igneous intrusions, etc. Such information is vital to deconvolving the depositional, erosional and tectonic history of the crust. To provide a high level of confidence that the record revealed by such drilling investigations has regional, rather than just local, significance will likely require reaching depths that range from ~100 m to as much as 1 km or more.

C. Nature and Distribution of Oxidants as a Function of Depth.

Analysis of Martian soil samples by the Viking Landers indicated the presence of a powerful oxidant in the near-surface regolith. Although various candidates have been proposed (such as hydrogen peroxide, metal oxides and peroxides (e.g., MnO_2, Mn_2O_2), and oxygen radicals), the nature and distribution of this oxidant is unknown. Therefore, it is expected that the characterization of the oxidant by drilling will provide valuable information on the evolution of the regolith, atmosphere-surface interactions, and its influence on the distribution and stability of organic compounds. The nature and distribution of oxidants and the depth at which oxidation effects disappear can also influence the operations of humans on the surface, as the oxidized materials appear to be the most reactive and potentially toxic/irritating to humans. Several instruments are being developed that may be able to characterize and quantify the oxidant (see Appendix II). Although the depth to which the oxidant has interacted with regolith is unknown, theoretical calculations suggest that its abundance may decline rapidly at depths in excess of a few meters. Thus, drilling to depths of ~10-20 m should encompass that region of the crust that reflects its present-day distribution.

D. Organic Compounds & Other Potential Biomarkers.

Our knowledge of the origin and evolution of life on Earth, combined with what we know of the geologic and climatic history of Mars, suggests that if a native biota ever evolved it was most likely carbon based. Organic compounds are important byproducts of both pre-biotic and biotic processes, although their detection would not, in and of itself, indicate that life had evolved on Mars. However, no organic compounds were detected in the soil samples analyzed by the gas chromatograph/mass spectrometer on the Viking landers, whose detection limits were on the order of parts per billion for heavy organics and parts per million for light organics.

This failure to detect organic material in the soil, places an upper limit on the presence of organics that appears to be less than that expected solely from the influx of carbonaceous chondrites. This absence of organic compounds is apparently the result of a potent oxidizing agent whose presence was detected at both Viking lander sites (Section III.C). The nature and genesis of the oxidizing agent is not well understood, but one model suggests that solar UV, acting on the small amount of water vapor present in the atmosphere, may create peroxides in the soil (Yen et al., 2000). Because there is little evidence for extensive reworking of the planet's most ancient (~3.8 b.y. old) terrain, the distribution of the oxidant is expected to be controlled by molecular diffusion and, thus, its present occurrence is expected to be limited to a depth of several meters. For this reason, the inability of the Viking Landers to detect organic compounds in surface samples does not exclude the possibility of organic matter existing at greater depth beneath the surface. Indeed, as noted earlier, it appears that some minimum level of organic material should be present simply from that brought in and mixed with the regolith by cometary and meteoritic bombardment. Therefore, whatever analytical abilities are used to detect oxidants and organics, they should be employed at frequent (~30 cm) depth intervals within the shallow (<5 m) subsurface to help identify any gradient in molecular concentration that is indicative of the diffusive transition from the oxidizing surface conditions (Appendix I).

Clearly, the discovery of organic matter on Mars would be an extremely important finding with particular significance to exobiology – providing potential insight into the origin and evolution of life, not only on Mars, but in a much broader planetary context. But what distinguishes an unambiguous biomarker (i.e., a signature of past, or present, biological activity) from an abiotically produced substance?

In planning for future Mars missions, and specifically any drilling investigation associated with '07 opportunity, a variety of reliable biomarkers must be identified. The term "biomarker" encompasses a wide range of substances including specific classes of organic compounds, isotopic ratios of C, N and S, fossilized remains of once living organisms, and minerals produced by living systems (also known as "
Biomarker geochemistry is a standard tool in petroleum exploration and is based predominantly on the identification of geologically stable organic molecules, often lipids, of known biosynthetic origin. Samples acquired at intervals within the uppermost regolith, and especially within (or beneath) ice-saturated regolith, are expected to provide the best chance for preserving evidence of life.

E. Geophysical Environment.

1. Heat Flow and Thermal Properties.

Knowledge of the thermal evolution places constraints on the bulk abundance of radioactive elements and, more loosely, on the history of the release of volatiles (water and atmospheric gasses) to the surface. The thermal gradient is an important factor in determining the mobility and stability of volatiles, as well as rates of reaction, as a function of depth. Differences in heat flow between geologic environments indicate significant differences in composition and/or level of geologic activity. If the heat flow could be measured accurately at several latitudes it should be possible to estimate the induced climatic heat flow variations (Mellon and Jakosky, 1992). As part of the heat flow experiment, the soil thermal conductivity must also be measured. Under Martian conditions, the soil conductivity is largely a function of porosity, grain-size, composition, the extent of induration and the presence of volatiles (adsorbed or present as ice in the crustal pores).

This objective falls under 'determine the chemical and thermal evolution of the planet in the MEPAG document, (III.B.3, priority 3).

Science questions:

- What is the near-surface thermal environment?
- What is the present day heat flux from the interior?
- What is the implied depth to liquid water?
- What is the implied thermal history of the planet and the radioactive heat budget?

To determine the interior heat flux to an accuracy of ± 5 mW/m^2, multiple heat flow measurements in a given geologic environment are required to average out local variations due to topography and subsurface variations. A single measurement would have some interest, but would also have very large error bars. On the moon, two heat flow measurements were made within several hundred meters of each other and differed by a factor of two (Langseth et al., 1976). Ideally three or more measurements should be made in holes spaced 10s to 100s of meters apart, at depths that extend below the annual skin depth (but to determine the geothermal gradient, these temperature measurements should also extend all the way to the surface).

The depth of the annual wave is a function of the soil/rock thermal conductivity, with rock and large grain-size soil having larger values of conductivity than small grain-sizes. Thus for rock, the ideal depth would be approximately 5-6 m. For very fine grained soil, the internal heat flux may dominate the temperature at depths as shallow as 2 m. A likely depth in 'typical' Martian soil is 3-4 m. The temperature gradient could be measured by a cable linking a series of sensors left in the hole following completion of other experiments. As drilling itself may disturb the local temperature profile, it may take days to weeks for the soil temperature to reequilibrate; therefore, a power source capable of supporting data collection over an extended period may be necessary. Alternatively, it may be possible to mitigate the magnitude of the thermal disturbance caused by drilling by appropriate adjustments to the level and duration of applied power.

2. Seismology.

2A. Passive Seismology -- A variety of high priority science objectives (Solomon et al., 1991) described in the MEPAG document could be met with a seismic network, including determination of geologic processes through constructing the stratigraphic column, evaluating igneous processes and their evolution, structure of

the dichotomy, determining the tectonic history, characterize the interior structure, and calibrate the cratering record. Given the deployment of the four NetLanders in '07 (Lognonné et al.,, 2000), which will carry both short and long period seismometers, the opportunity to augment the seismic network is tremendously important. The expansion of this seismic network from four to five stations would vastly enhance its ability to determine the structure of the crust and mantle, the state of stress in the lithosphere, and the current levels of tectonic and volcanic activity on Mars.

Science questions:

- What is the thickness of the crust?
- What is the present day level of geologic activity?
- What is the structure of the near surface layers?

2B. Active Seismology -- In addition to the objectives that can be met via a global network, a local, active network, such as ~10 seismometers separated by 10's to 100's of meters (depending on the depth to be probed) would have a separate set of valuable science objectives. These include determining the local depth to water, providing ground truth for orbital radar, and creating a site survey and local context to relate the measurements from one hole to another.

2C. Deployment Considerations -- A seismometer is best deployed at a depth of 1-2 m, so that it is well protected from diurnal thermal variations and vibrations due to wind. Very small, low power seismometers have been developed for planetary applications (Banerdt et al., 1996). . In order to augment a global network, only 1 (3-axis) seismometer is required, but itmust have its own power and communications with an orbiter for a period of at least 1 Martian year. For a local network, surface deployment is sufficient. An active source is necessary, and could consist of a mechanical thumper (for shallow structure, 10's of meters) or several explosive charges (for deeper penetration, up to a km). At least ten sensors would be required, with a spacing depending on the depth to be probed. Additionally, determining the seismic attenuation of the crust would help with interpretation of orbital radar sounding data.

3. Electromagnetic Properties.

In-situ determination of the electromagnetic and seismic properties of the crust (in addition to a knowledge of its composition and thermophysical properties) would be an invaluable aid to interpreting the data returned by orbital radar sounders and surface-based geophysical networks. It would also provide valuable input for the design of future geophysical investigations. If there is a sufficient source, either in the form of electrical discharge from the atmosphere or an intrinsic magnetic field, it may be possible to use magnetotelluric methods to conduct local sounding in the drill area.

4. In-Situ Stress, Strain, and Material Strength.

Measurement of stress and strain in a drill hole would help to determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration etc.) that have created and modified the Martian crust and surface (MEPAG, III, A, 7).

This measurement requires drilling in competent bedrock. It is made by taking an over core of the initial hole, and measuring the deformation of the extracted disk. It may also be possible to measure the deformation of the drill hole itself. Repeating the measurement in another hole would be a good check, but the tectonic stress should not vary significantly over scales of kilometers.
The drill can measure soil bearing strength and surface penetration through the measure of the torque needed for penetration and from penetration velocity. The measure of these parameters is explicitly recommended by MEPAG.

5. Radiation Environment.

Drilling a hole into the subsurface allows the emplacement of radiation detectors with which the shielding properties of the regolith can be determined. Because the incidence of cosmic rays on the surface and the production of neutrons in the atmosphere, there will be a significant flux of neutrons and in the subsurface that represent a potential environmental hazard for long duration missions. The neutron intensity at depth is a complex function of the incident radiation and regolith composition, requiring in-situ measurements to about 3 meters.

IV. Downhole vs. Surface Analysis

How much of the science/analysis can be done down-hole? Is there a significant benefit to bringing drill samples up for analysis by instruments on the rover/lander?

For the potential drilling investigations identified by MEPAG (i.e. geochemical and organic analysis, stress and strain determination, etc.), the drilling system must incorporate an *in-situ* analysis package to be used either downhole or – if a suitable sample acquisition, preservation and transport
the surface.

Downhole science can identify boundaries between different stratigraphic units, determine the composition and granularity of different layers, and identify the mineralogy of individual grains through dedicated miniaturized instruments, that can be incorporated directly into the drill. In addition, temperature and thermal diffusivity sensors, radioactivity dosimeters and spectrometers, resistively and/or dielectric constant sensors can also be accommodated. However, the sensitivity and precision of subsurface instruments will always be limited by the mass, power and volume required for analysis. Even more problematical is the time required for analysis, which may be minutes to hours for the analytical devices that currently exist for planetary surface analysis. This analytical time could conflict with drilling time.

Instruments at the surface are likely to have greater range of detection and sensitivity than instruments placed into the drill hole; however, the need to bring documented samples to the surface and deliver them to instruments increases the complexity of the drilling activity. Some materials from drilling will naturally reach the surface; however, they may not provide precise definition of unit boundaries. Nevertheless, for drill holes greater than a few meters in depth, where precision of contact depths becomes less important, analyzing

samples at the surface should be included. As mentioned above, any deep holes drilled may encounter units that can not be sampled at the surface (other than, perhaps, as crater ejecta for which the original stratigraphic context is unknown). The advantage of sampling them with a drill is that their context can be established, allowing better understanding of the relationships between units, thickness of units, etc. Therefore, provision should be made for retaining subsurface samples in some semblance of their original stratigraphic position for future study.

A list of potential instruments for surface and subsurface applications is presented in Appendix II.

V. Sample Size and Handling Considerations

If samples must be returned to an automated station on the surface, must they be cored or can they be cuttings (and, if cuttings, what size)? Are there any sample handling concerns, such as limits on thermal or mechanical alteration, or exposure to the atmosphere (e.g., as would be the case in determining the amount of adsorbed volatiles)?

For a mission equipped only for in-situ experiments (i.e., not returning samples to Earth) drill cuttings a few millimeters in diameter would be sufficient for sample analysis. Although textural relationships (e.g. detailed stratigraphy) are more easily seen in cores, they can be deduced from cutting-sized fragments if necessary. For this reason, cored samples are not required if the capability to properly acquire, preserve and transport such a sample does not exist, or the samples are being stored for return and analysis on Earth. For analysis on the surface of Mars, the use of cuttings does not appear to be a major problem because, for most experiments, the samples would need to be even further crushed to prepare them for analysis.

Beyond the precautions that must be taken to insure that samples are not highly contaminated by the drilling process, a principal objective of sample handling should be to preserve (to the extent possible) the stratigraphic relationships of the cuttings. This could be done by conducting in-situ analysis downhole or by taking samples and returning them to the surface at specific intervals, rather than continuously. However, a capability to preserve a continuous sample (even if it is just laid out on the Martian surface) would be highly desirable, if a means of inspecting and sampling this material in stratigraphic context could be developed.

The two types of investigations most likely to require environmental control are analyses of organic and volatile content. In the case of organics, the primary handling concern (assuming $T \leq 273$ K) is contact with any potential oxidant that may be present in the atmosphere or at the surface. For volatiles, gaseous isolation is vital, as direct communication with the atmosphere could result in the rapid depletion of adsorbed, liquid and solid phases. In addition, to insure an accurate assessment of the original phase partitioning and volatile distribution in the sample, a tight control must also be maintained on preserving the original conditions of pressure and temperature that characterized the environment from which the sample was obtained. Failure to maintain these conditions (within tolerances on the order of 1%) could lead to substantial changes from the volatile's original state, a potential that appears particularly great with respect to adsorbed gases and gas hydrates. Because the drilling process itself may induce such changes, some mechanism of continuous thermal monitoring and control should be considered.

VI. Science Return vs. Drilling Depth

How would our science objectives/return differ if we had the ability to drill to 1-5, 10-20, or 50-150 m depths? Of particular concern are those related to water and life.

The subsurface stratigraphy of Mars is both uncertain and likely highly-variable. The potential scientific return from a drill hole is, to a first approximation, related to the number of distinctive stratigraphic units that are encountered and analyzed. The following table summarizes some of the principal characteristics that may enter into the determination of optimum drilling depth.

Stratigraphic Unit	**Depth range**
Propagation depth of diurnal thermal wave	0.15 – 0.3 m
Depth of eolian modification (sand dunes, wind blown dust)	0 - 5 m
Propagation depth of annual thermal wave	2 - 6 m
Zone of surface/atmosphere interaction (volatile transport and oxidation zone)	0 - 10 m
Regolith (the disaggregated material that has resulted from meteoritic impact, weathering and erosion)	0 – 10 m, with the potential for additional thicknesses interbedded between volcanic and sedimentary units at depth
Bedrock	Below the regolith
Stability of gas hydrates	~15 m – several km
Massive ice lenses	~20 - 1000 m
Cryosphere (that region of the crust where T< 273 K)	Is believed to generally extend to depths of 2.5 – 5 km at the equator, and up to 8 – 13 km at the poles.
Liquid water	May be absent or present from zero to many km beneath the cryosphere

Viking Orbiter and Mars Global Surveyor images have shown that stratigraphic layering (of unknown origin) is widespread on Mars and may have large lateral extent. Sedimentary, volcanic, and ejecta deposits may be intermixed, with numerous interbedded layers of regolith. Thus, depending on location, the deeper the hole, the more likely it is that a succession of stratigraphic units will be encountered.

Drilling investigations of less than ~1 m would generally allow characterization of the physical properties of the uppermost regolith; however, it appears unlikely that the scientific yield from such efforts would considerably differ from that obtained by a robotic arm. For HEDS-related issues and for more general studies of composition, physical properties, and seasonal- and climate-induced atmospheric-regolith exchange, depths of ~5-10 meters are probably sufficient.

The probability of encountering massive ice lenses appears low for depths of less than 20 m, while – in the absence of local geothermal anomalies – the occurrence of liquid water is likely restricted to depths in excess of several kms.

For most science objectives, the greater the depth of penetration the better – a conclusion based on the greater access it provides to understanding the local geologic record. For this reason, and because of the insights gained from obtaining a sample in stratigraphic context, it appears there is more to be learned from the analysis and sampling of 100 m of vertical stratigraphy than from a horizontal traverses of the same distance.

VII. The Importance of Mobility

How important is mobility? What advantages would there be to having a rover that could drill at multiple locations? Would it be worth sacrificing a roving capability to land a more capable/deeper penetrating drill? What happens if we land on coherent rock (or encounter it at very shallow depth)?

Mobility would be an asset in optimizing the location of a drill. The ability to traverse distances ranging from a few, to as much as several hundred, meters may be important if a lander arrives in a location where drilling is either impossible or inconvenient (e.g., on a steep slope or on top of a boulder), or if some experiments (such as heat flow measurements) require the drilling of multiple holes.

Still greater mobility, up to several kilometers, would be useful in targeting specific sites within the mission's landing ellipse (3-6 km in the case of Mars 2007). This level of mobility would permit the selection of an optimum drill site from remote sensing and geophysical data, in advance of landing, and provide reasonable assurance that the drill could actually reach its intended target.

On the other hand, it may be possible to select sites where extended mobility is not important. For example, much of the stratigraphy observed in orbital images is horizontally extensive. On such terrain, the advantage of lateral mobility is significantly reduced, because the types of rocks encountered at depth will likely be similar wherever within this region they are actually obtained.

However, the greater the depth capability of a drilling system, the less likely it is that it will be integrated into an exploratory rover, due to both its greater mass and power requirements and because of fundamental differences in mission. For example, drilling to any significant depth could easily require weeks, months, or years at a single site – durations which are generally incompatible with the goals of mobile surface exploration.

As noted in the preceding section, for most scientific objectives and most sites, having a greater depth of penetration appears more advantageous than having greater surface mobility. However, if a drilling system has limited (or no) mobility, it is critical that it be capable of stable operation on non-ideal surfaces and be able to penetrate boulders up to ~1-2 m in diameter. Ideally, it would also be desirable to determine whether any rock encountered at depth was a boulder or part of an in-situ stratigraphic formation; however, such a judgement would be extremely difficult to make without a local geophysical survey

VIII. Conclusions/Recommendations

Based on the preceding analysis, we have reached the following conclusions regarding the potential science return and feasibility of subsurface drilling as part of the proposed 2007 mission:

Depth of Penetration:

For overall science value, the greater the depth of penetration by a drill, the better. However, the science value does not go up uniformly with depth. There are three primary breakpoints in the issue of science return vs. depth of drilling:

- 1-5 m
- 10-20 m
- 50-150 m

Considering that almost nothing is known on Mars subsurface, investigations extending to depths of 1-2 meters would provide important information regarding the regarding regolith physical properties, petrology, and volatile transport. By going to 3-5 m, the interior heat flux can also be readily measured.

However, the science value of subsurface access goes up dramatically at 10-20 m. This depth is sufficient so that there is a reasonable chance of penetrating below the surface oxidized layer (estimated to range from ~1 - 10 m), which would enable critical studies of the presence of organic molecules and other potential biomarkers. This depth would also provide improved measurements of internal heat flow, and it may also be sufficient to reach ice-saturated frozen ground (depending on the latitude and local physical properties of the landing site). The probability of accessing bedrock increases substantially with depth and appears likely in a 50-150 m hole (enabling studies of bedrock geology). More importantly, depending on the landing site, a 50-150 m hole may intersect segregated bodies of massive ground ice (e.g. formed by the outflow channels or a primordial ocean), and it would likely access a significant region of ice-saturated frozen ground.

In summary, we recommend that every effort be made to achieve a minimum penetration of 20 meters, because this will supply data that are critically needed to plan future investigations. However, in the event that reaching such depths is not feasible with present technology, investigations to depths of as little as a few meters would still provide significant opportunities for improving our knowledge of Mars

Importance of Multiple Holes:

For most of the subsurface science issues identified by MEPAG, the potential return from a single deep hole is considered more valuable than from multiple shallow holes. However, if other factors constrain the maximum drilling depth to <5 m, then the capability to drill multiple (~3-5) holes becomes more desirable -- adding significant confidence to the characterization of local near-surface properties.

Value of Mobility:

For drilling missions to depths ³ 10 m, a limited degree of mobility (i.e., from ~1 to several 10s of meters) would be useful (but not mandatory) to optimize the specific place where drilling will begin. Greater mobility would be desirable if the maximum drilling depth is shallow (< 5 m), to insure that the measured properties are representative of the targeted area. Mobility of as much as several kilometers would be necessary if the desired subsurface target occupied only a small fraction of the mission's landing ellipse.

Value of Retrieving a Sample for Surface Analysis:

Some kinds of investigations will require that samples be delivered to the surface for analysis, while others will require measurements that can only be made in-situ in a borehole. In some instances, investigations could be conducted by either approach. For most life-related investigations, sample retrieval is necessary given the current state of technology. However, down-hole analysis is preferable for assessing volatile saturation and state, and this mode is mandatory for recording heat flow and seismic data. Most geologic questions (composition, lithology, porosity) can be answered in either mode. We believe that a reasonably complete drill-related science package will need to include a mix of these capabilities.

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Appendix II: Summary of Potential Instruments to Support Subsurface Drilling in '07

1. Science Objective: Composition & State

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Elemental	APX Alpha-Proton-X-ray	APXS R.Rieder	570 g 340 mW	9	Mars Pathfinder ATHENA Payload, Mars 2003
	Gamma Ray Spectrometer (passive)	GRS W. Boynton	25 kg	8	Mars Observer (Orbitor)
		Lunar Prospector GRS W.C. Feldman	2 kg 1 W	9	Lunar Prospector
		NEAR GRS J. Trombka	XRS/GRS 27 kg 31 W	9	NEAR (Near Earth Asteroid Rendevous)
	Neutron Activated GRS (active source)	Neutron Activation GRS J. Bradley J. Schweitzer	5 kg 5 W	3	JPL-Schlumberger-Doll
	Laser Induced Breakdown Spectrometer	LIBS D. Cremers	1.5 kg 3 W	5 ~ 6	MIDP Developed Field Test, May 2000
	X-Ray Fluorescence	MA_FLUX R. Bianchi	1.35 kg 4.5 W	5 ~ 6	Mars 2003 Sample return Mission
		XRF B. Clark	4 kg 5 W	9	Viking (1977)
		XRF B. Clark	1 kg 3 W	6 ~ 7	PIDDP (1990)
		NEAR XRF J. Trombka	XRS/GRS 27 kg 31 W	9	NEAR (Near Earth Asteroid Rendevous)

1. Science Objective: Composition & State (continued)

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Mineralogy	UV-VIS Spectrometer	Clementine UV-VIS Camera L. Pleasance (LLNL)	0.3 kg 2 W	9	Clementine Mission
	FT-IR Spectrometer	Mini-TES P. Christensen	2.5 kg 5 W	6	ATHENA Payload Mars 2003
	Imagin IR Spectrometer	IRMA Infrared Spectrometer/micro-scope F. Capaccioni	1.4 kg 8.8 W (peak)	6-7	Mars 2003 Sample return Mission
		AimS D. Glenar	2 kg 12 W	5	MIDP Developed
	Raman Spectrometer	Raman L. Haskin	3 kg 12 W	6	Mars 2007?
		Fiber Optic Raman C. Schoen	1 kg 5 W	5 ~ 6	MIDP Developed
	X-Ray Diffraction Spectrometer	XRD/XRF D. Blake	2 ~ 4.5 kg 3 W	4	PIDDP, SBIR (Moxtek)
		XRD/XRF J. Marshall		3	
	Differential Scanning Calorimeter Evolved Gas Analyser	TEGA (DSC+EGA) W. Boynton	4 kg 30 ~ 35 W	8	MVACS-Mars Polar Lander, 98
	Moessbauer Spectrometer (Iron Phase Mineralogy)	Moessbauer G. Klingelhoefer	0.5 kg 1.6 W	7	ATHENA Payload Mars 2003

1. Science Objective: Composition & State (continued)

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Organic & Volatiles	Mass Spectrometer Quadrupole	Huygens GCMS H.B. Nieman	17 kg 15 ~ 25 W	8	Galileo-Huygens Probe
		CHARGE GCMS P.R. Mahaffey	3 ~ 9 kg 5 ~ 25 W	6	Champollion Payload (Simpler version of Huygens GCMS)
		Quadrupole Mass Spectrometer A. Chutjian	1 kg 10 W	9	PIDDP Shuttle Astronaut Tool (Code U)
	Mass Spectrometer Magnetic Sector	Regolith Evolved Gas Analyzer (REGA) J. Hoffman	7 kg 30 W	5 ~ 6	MIDP Developed
		Miniature Mass Spectrometer M. Sinha	1 ~ 2 kg 2 W	4	PIDDP/CETDP
	Organic Detector	Mars Organic Detector (MOD) J. Bada	2.5 kg 24 W	5	MIDP Developed.
Oxidants	Oxidant Detector	Mars Oxidant Instrument (MOI) A. Zent	1.5 kg 1 W	4	Under MIDP Development Beagle 2?
		Miniature Electron Paramagnetic Resonance (EPR) S. Kim	1.5 kg 1 W	4	PIDDP SORBE (Soil Reactivity and Biological Effects) HEDS 2005 Definition Study, PI. A. Yen
		Charge Distribution Probe (CDP) F. Freund	1 kg 10 W	3 ~ 4	PIDDP

2. Science Objecitve: Lithology and Thermophysical Properties

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Particle/Crystal Size	Electron Microscope X-ray analyzer Particle Size Analyzer	SEMPA (Scanning Electron Microscope and Particle Analyzer) A. Albee	12 kg 22 W	4	PIDDP
Density/Porosity/ Permeability	γ-ray spectrometer	GRS (Champagne) W/ Cs source T.J. Ahrens C. d'Uston	1.5 kg	4	Champollion Physical Properies Probe (CPPP)
Thermal Conductivity/ Heat Capacity	Set of Thermisters	Mast_Pro Gori	450 g	4	Mars 2003 Sample return Mission
		Thermal Conductivity Experiment S. Smrekar	10 g	4	DS-2/PIDDP
Seismology	Micro-seismometer	SEIS-SP W.B. Banerdt	50 g 40 mW	5	Selected for Netlander 2007
Radiation	Radioactivity Dosimeter	Mare-Dose C. Federico	530 g 6.5 W (peak)	4	Mars 2003 Sample return Mission
Atmosphere	Dust Detector	MAGO L.Colangeli	1.45 kg 6.1 W	7 ~ 8	Mars 2003 Sample return Mission
	Sensors for Pressure/Temp ./Wind speed/Wind direction/Water vapor /CO_2 Isotopic Ratios (TDL,$^{13}C/^{12}C$, $^{18}O/^{16}O$, D/H)	MET (Meteorology Package) D. Crisp	3.2 kg 5 W	8	MVACS Mars Polar Lander

3. Science Objective <u>Imaging/Microscopy/Petrography</u>

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Imaging Microscopy	Microscope	IRMA Infrared Spectrometer/microscope F. Capaccioni	1.4 kg 8.8 W (peak)	6 ~ 7	Mars 2003 Sample return Mission
		Camera Hand lens Microscope (CHAMP) G. Lawrence	500 g 2 W	5 ~ 6	MIDP (Under Development) Field Demo, June 2001
		Microscopic Imager K. Herkenhoff	0.22 kg 3 W	6	ATHENA Payload Mars 2005
Borehole Camera	Near IR Imaging Spectrometer (borehole)	Ma_Miss A.Coradini	840 g 4.5 W	5 ~ 6	Mars 2003 Sample Return mission drill
	Borehole IR Spectrometer/microscope	CIRCLE R.V. Yelle	600 g 5 ~ 10 W	4	Champollion IR and Camera Lander Experiment

4. Science Objective: Subsurface Characterization

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Subsurface Characterization	Subsurface Sounder	MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) G. Picardi/W. Johnson	17 kg 70 W	7 ~ 8	2003 Mars Express Orbitor
		Ground Penetrating Radar (GPR)- Impulse John A. Grant		4	PIDDP
		MASTER (SubSurface Radar) Tacconi	580 g 3.55 W	4	Mars 2003 Sample Return mission drill
		Miniature GPR- Range Gated Step Frequency S.S. Kim (JPL)	1 kg 5 W 200 m depth	4	PIDDP (99-01)
		Electromagnetic Sensor I.J. Won (Geophex)	0.5 kg 1 W 5-10 m depth	4	Under SBIR development, 2001
	Subsurface electric properties	ACQUA S.Orsini	420 g 0.05 W	4	Mars 2003 Sample Return mission drill

5. Science Objective: Sample Acquisition & Delivery

	Instrument Type	Example/PI	Mass Power	TRL	Comment
Sample Acquisition/ Delivery	Robotic Sampling/Device	SAS E. Re (Tecnospazio)	3.8 Kg 12 W (26 samples)	7 ~ 8	ROSETTA Lander
		DeeDri E. Re (Tecnospazio)	12-15 kg 5-30 W (10-50 samples)	5 ~ 6	Mars 2003 Sample Return mission drill
		Ultrasonic Drill/Corer (USDC) B. Dolgin Y. Bar-Cohen	0.4 kg 10 W	5	Development under Mars Exploration Technology
		Subsurface Sampling Tool H. Hamacher (Germany)	1 kg 4 W	5	MIDP Collaboration
		Abrasive Jet Polisher S. Fuerstenau	1.5 kg 0.1 W	5	MIDP developed
		Rock Abrasion Tool S. Gorevan (Honeybee)	4 kg 17 W	5	ATHENA Payload Mars 2003 (Sample Acquisition and Transport Mechanism Champollion DS-4)
		Pyrotechnique Rock Chipper A. Cheng (APL)	1 kg (10 Samples) 20 W (Peak)_	5	PIDDP
	Sample Management	IPSE SMS (Sample Management System) A. Angrilli	520 g 3 W	4	Mars 2003 Sample Return mission drill
	Sample Container	Sample Container B. Dolgin	0.5 kg 5 W	4~5	Development under Mars Exploration Technology

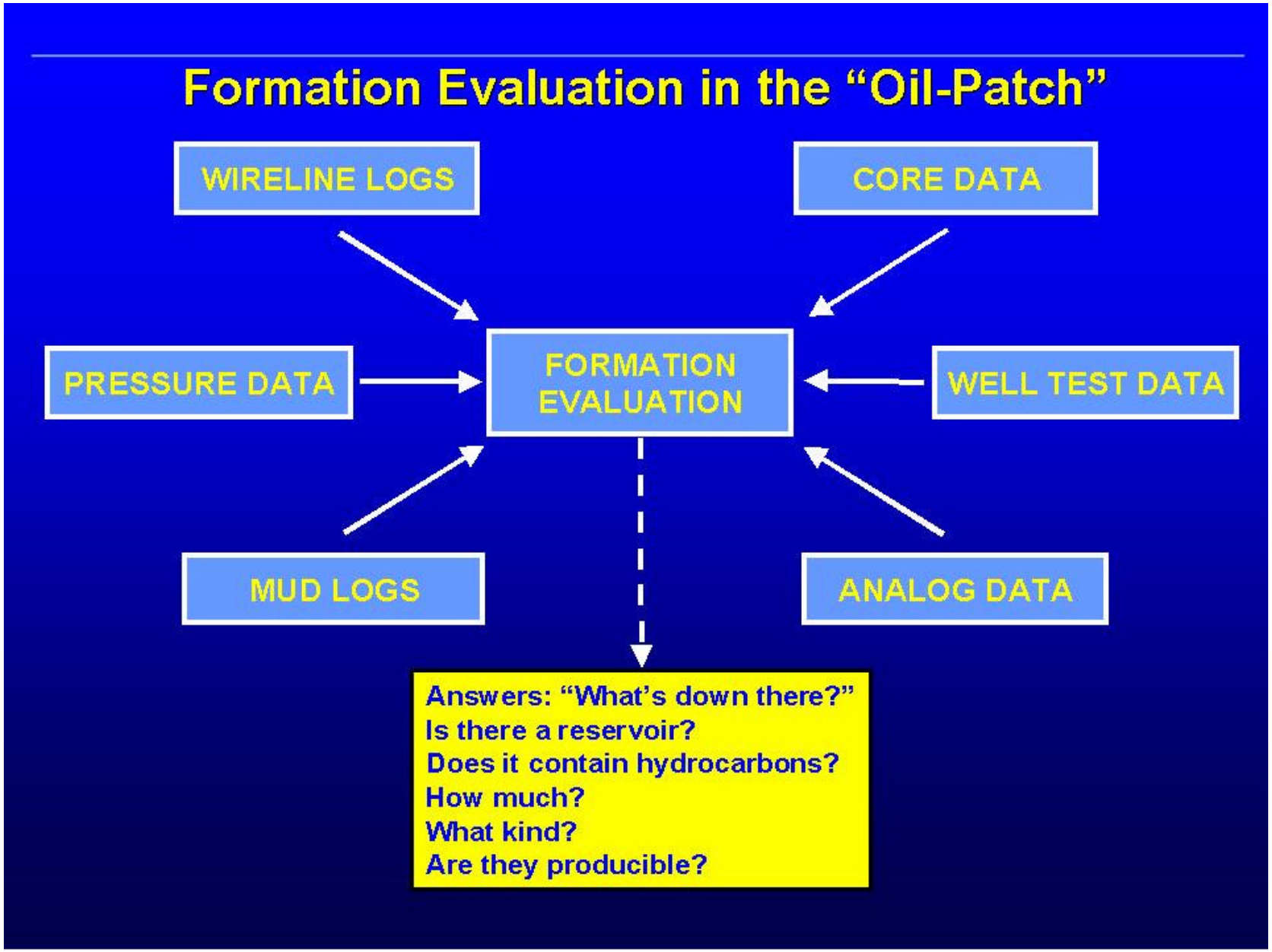
Appendix IIb: Bore-hole vs. Surface Instruments

	Science Requirements	Subsurface Volatiles					Crust Geology				Oxidant		Organics / Biomarkers	Geophysical Environments				
		Adsorbed /Chemically Bound (H2O, CO2,O2)	Liquid Water	Ground Ice	Saturated / Unsaturated Frozen Ground	Gas Hydrates (CO2, H2S, CH4)	Lithology	Mineralogy (Elemental, Chemical)	Physical Properties (Density, Particle Size)	Stratification	Characterization	Distribution as Depth		Heat Flow / Thermal Properties	Seismology	Stress / Strain, Boring Strength	Radiation Shielding	Electromagnetic Properties
Bore-hole Instruments / Sensors	Neutron/g-Ray Detectors (Passive)						•	•									•	
	Pulsed Neutron Activation GRS		•	•			•	•	•	•								
	Natural Radioactive Source (Cs-137) GRS		•	•			•	•	•	•								
	Set of Distibuted Thermisters													•				
	Radiation Detector/Dosimeter																•	
	Seismometer														•			
	Magnetometer																	•
	Drill Toque/Penetration Rate monitor															•		
	Borehole Spectrometer (IR,Raman)	•	•	•				•										
	Borehole Camera/						•	•	•	•								
Surface Instruments	Subsurface Sounder/Ground Penetrating Radar		•	•	•													
	APX/XRF						•	•										
	IR/Raman Spectrometer	•	•	•		•	•	•										
	DSC/EGA/TDL	•	•	•		•												
	XRD						•	•										
	Moessbauer							•										
	GC/MS	•	•			•							•					
	Organic Detector												•					
	Oxidant Detector										•	•						
	Microscope						•	•	•									

Sampling	**Sampling as a Function of Depth**									•		•						

Appendix III: Related MEPAG Goals, Objectives and Measurements. (Available as a separate downloadable file)

Appendix IV: Terrestrial Well Logging Techniques & Instrumentation (PPT presentation prepared by Quinn Passey)



What is a Log?

- **Definitions (from general to specific):**

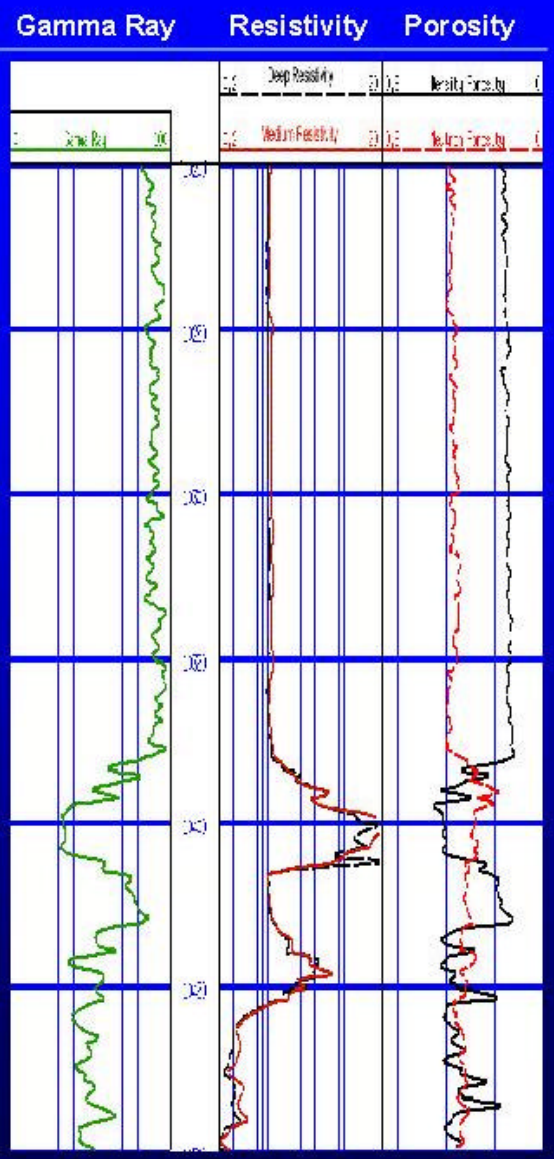
A *log* is "a record of measurements or observations..."

A *well log* is "A record of one or more physical measurements as a function of depth in a borehole."

A *wireline log* is "recorded by means of sondes carrying sensors which are lowered into the hole by a cable."

An *open-hole log* is recorded in a drilled borehole prior to casing and cement being set.

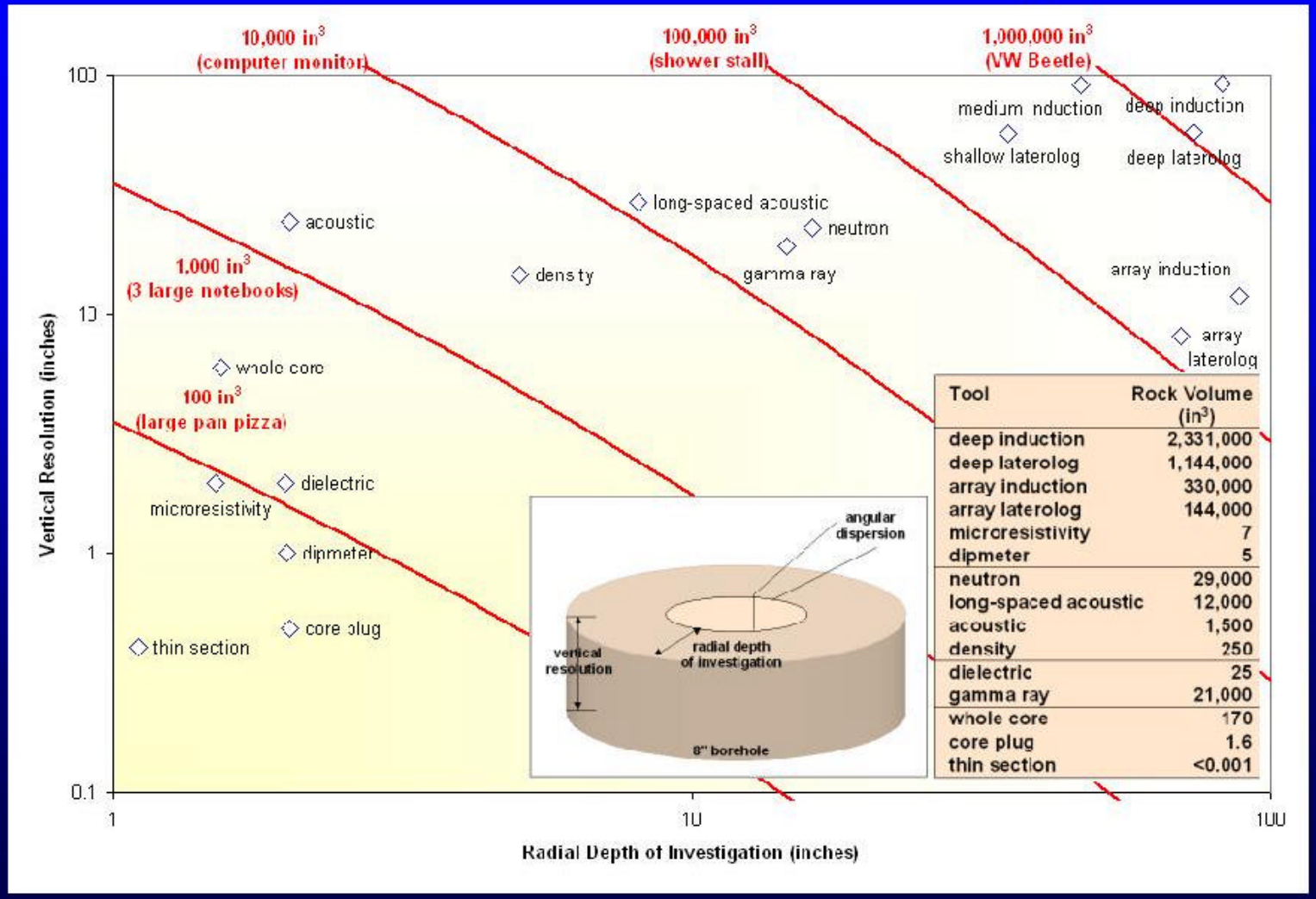
Other types of well logs are made of data collected at the surface; examples are core logs, mud logs, drilling-time logs, etc.



Matrix: Formation Property vs. Tool

	Gamma Ray	Spontaneous Potential	Sonic	Density	Neutron	Resistivity	Nuclear Magnetic Resonance	Photoelectric Effect	Wireline Testing	Well Test	Dipmeter	Borehole Image	Core
Lithology/Mineralogy	●	●	○	○	○	○	○	○				○	●
Porosity			●	●	●		●						●
Fluid Type				●	●	●	○		●	●			●
Fluid Saturation				●	●	●	○						●
Permeability		○	○	○	○	○	●		●	●			●
Stratigraphy	○	○									○	●	●
Downhole Pressure									●	●			

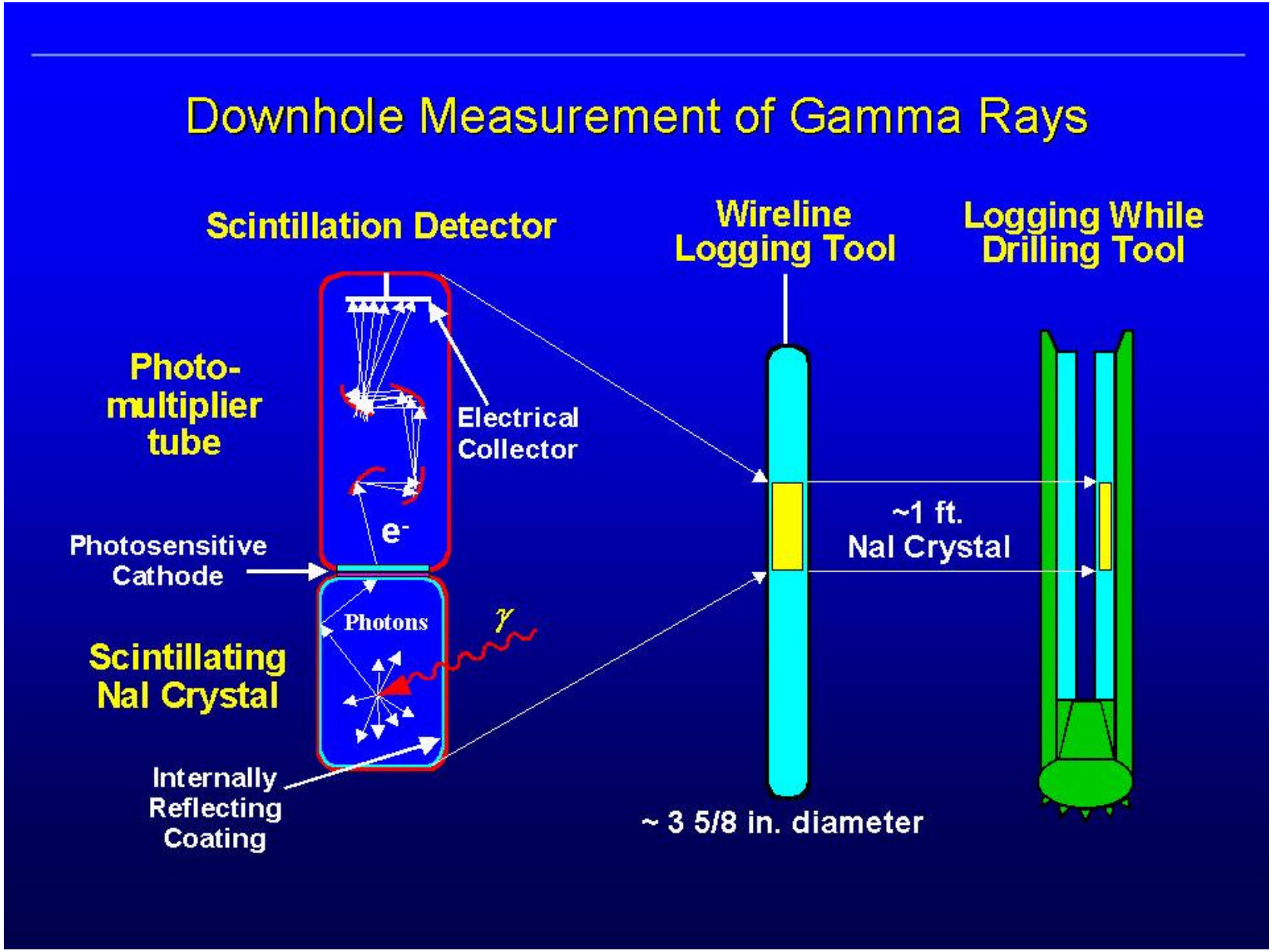
Tool Resolution and Volume of Investigation



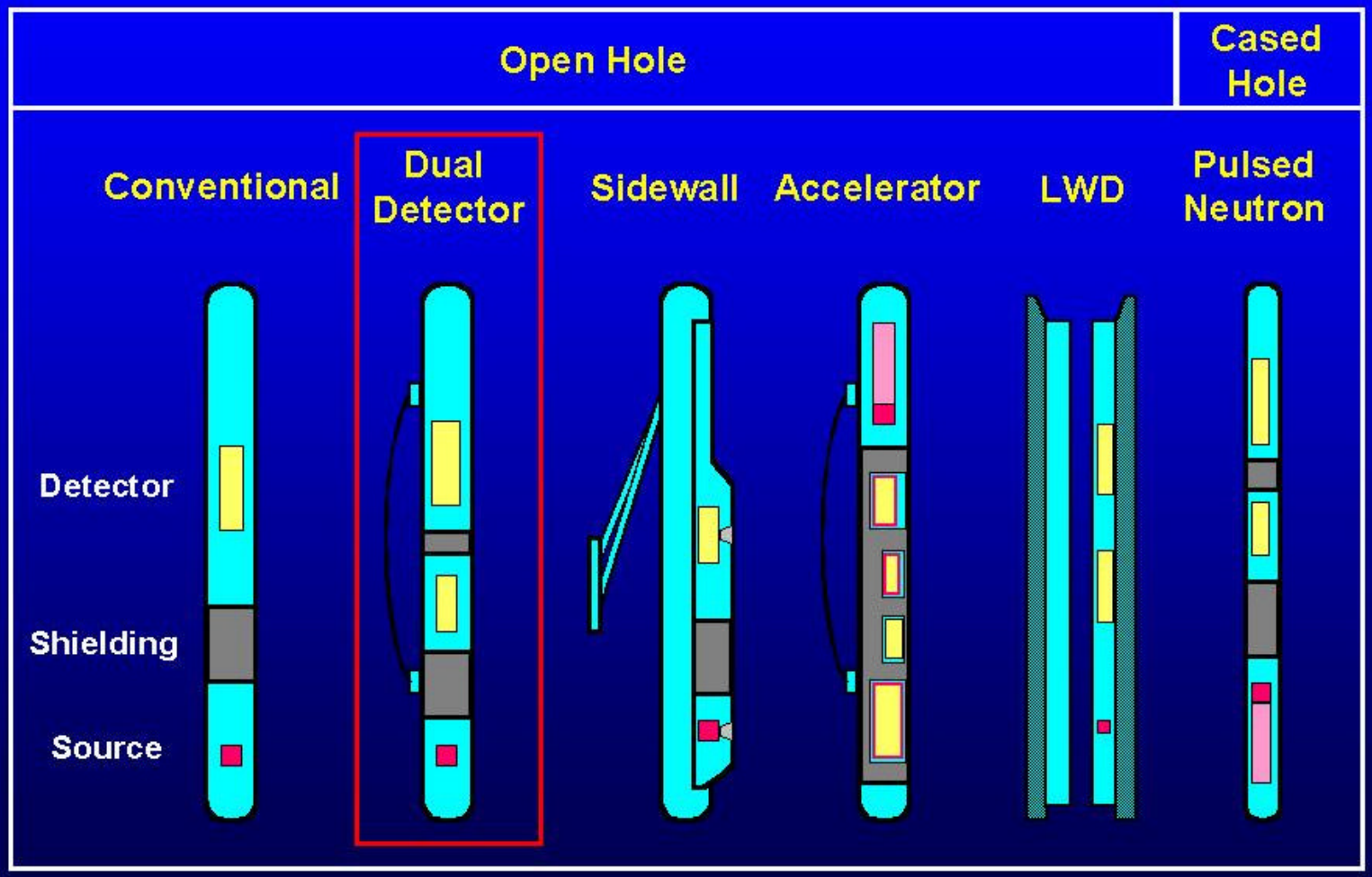
Tool	Rock Volume (in^3)
deep induction	2,331,000
deep laterolog	1,144,000
array induction	330,000
array laterolog	144,000
microresistivity	7
dipmeter	5
neutron	29,000
long-spaced acoustic	12,000
acoustic	1,500
density	250
dielectric	25
gamma ray	21,000
whole core	170
core plug	1.6
thin section	<0.001

Lithology and Stratigraphy

- Gamma Ray
  - Measures natural radioactivity of the formation.
  - Shales contain K, Th, U
  - Sands don't contain K, Th, U
- Spontaneous Potential
  - Measures voltage from flow of ions through permeable formations.
  - Sands are permeable
  - Shales are impermeable
- Combination of Sonic/Density/Neutron
  - Infered from elastic, density, photoelectric, and neutron absorption
- Neutron Activation
  - Elemental concentration (O^{16}, Na^{23}, Al^{27}, Si^{28}, Cl^{37}, Ca^{48}, Fe^{56}, I^{127}, Gd, H, C)
- Borehole Imaging
  - Electrical, acoustic, or video images of borehole wall
- Core
  - Direct sampling of reservoir lithology


Downhole Measurement of Gamma Rays
Scintillation Detector
Wireline Logging Tool
Logging While Drilling Tool
Photo-multiplier tube
Electrical Collector
e-
Photosensitive Cathode
Photons
γ
Scintillating NaI Crystal
Internally Reflecting Coating
~1 ft. NaI Crystal
~ 3 5/8 in. diameter

Generic Types of Neutron Porosity Tools



Neutron Activation Characteristics of Important Nuclei

Target Nucleus	Activation Product	Product Half-Life	γ Energy (MeV)
O^{16}	N^{16}	7.1 sec	6.13, 7.12
Na^{23}	Na^{24}	15 hr	1.37, 2.75
Al^{27}	Mg^{27}	9.5 min	0.84, 1.01
Si^{28}	Al^{28}	2.31 min	1.28, 2.43
Cl^{37}	Cl^{38}	0.37 min	1.6, 2.17
Ca^{48}	Ca^{49}	8.8 min	3.10, 4.05
Fe^{56}	Mn^{56}	2.6 hr	0.85, 1.81, 2.11, 2.52
I^{127}	I^{128}	25 min	0.44, 0.53

Overview of Borehole Imaging Tools

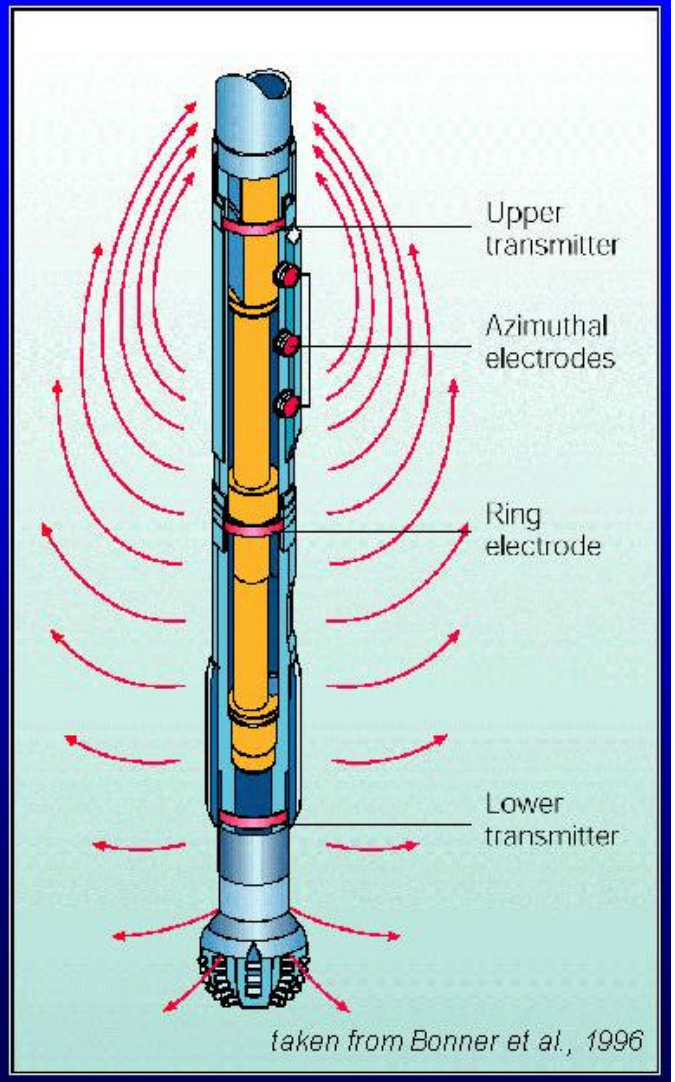
- **Electrical Imaging**
  - FMS (Formation MicroScanner)
  - FMI (Formation MicroImager)
  - EMI (Eletrical Microimager)
  - RAB (Resistivity At Bit)
  - STAR (Simultaneous Acoustic Resistivity Tool)
- **Acoustic Imaging**
  - UBI (Ultrasonic Borehole Imager)
  - CBIL (Circumferential Borehole Image Log)
  - CAST (Circumferential Acoustic Scanning Tool)
- **Low-Resolution Electrical Imaging**
  - Dipmeters
  - SHDT (Stratigraphic High Resolution Dipmeter Tool)
  - OBDT (Oil Based Dipmeter Tool)
- **Logging While Drilling**
  - GR
  - Density/Pe
- **Video Imaging**
  - Downhole video
- **Future**
  - Ground Penetrating Radar

Unwrapped borehole

Borehole Projection

Logging While Drilling Images

- Borehole imaging on the drill string
- Rotating of drill string causes azimuthal electrode to rotate
- Voltage measured as a function of time is stored downhole
- Image processing wraps the data into a borehole image after the drill string is pulled.



Porosity

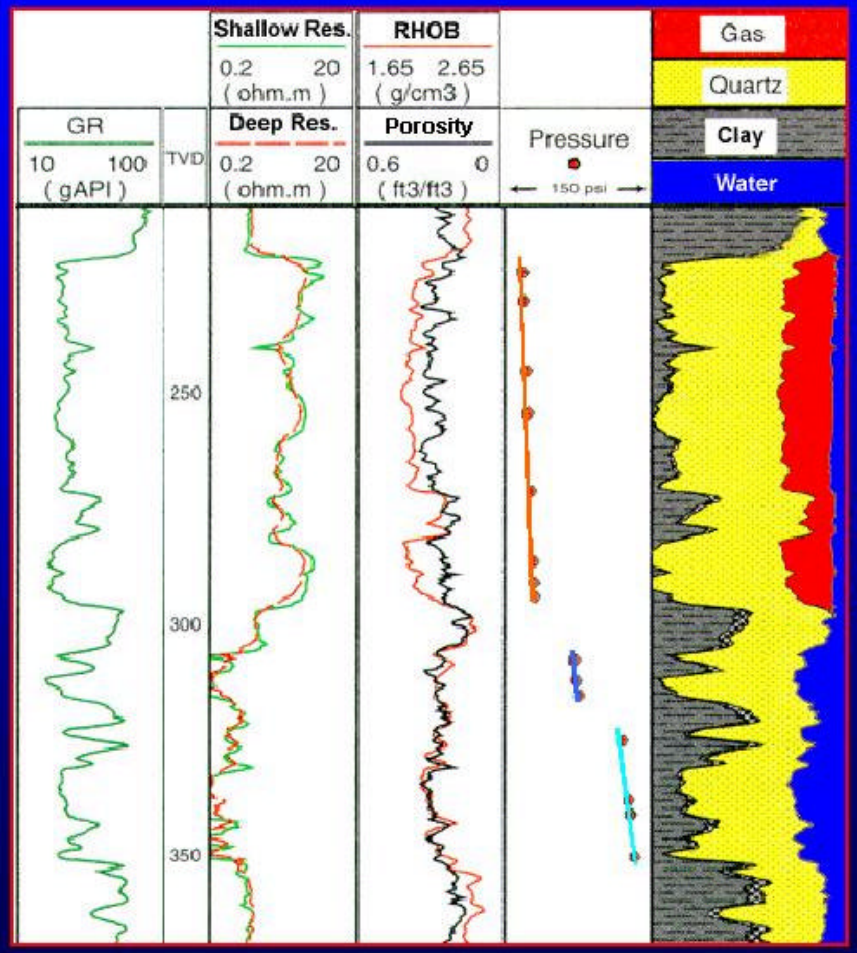
- Sonic
  - Porosity from travel time of acoustic wave propagating through formation.
- Density
  - Porosity from bulk density measured from scattering of gamma rays by formation; photoelectric absorption related to lithology
- Neutron
  - Porosity from absorption of neutrons by hydrogen in formation
- Nuclear Magnetic Resonance
  - Porosity from rate of precession of hydrogen protons in formation
- Core
  - Direct sampling of reservoir porosity

Fluid Type and Saturation

- Density/Neutron
  - Gas-bearing sands have high density porosity/low neutron porosity
- Resistivity
  - Hydrocarbon-bearing sands have high resistivity
  - Water-bearing sands have low resistivity
  - Calculations using Archie's Law to determine the water saturation and hydrocarbon saturation of the formation
- Wireline Testing
  - Direct sampling of reservoir fluids
- Well Testing
  - Direct sampling of reservoir fluids
- Core
  - Measurements of core properties provide variables used in the calculation that are not obtainable from wireline logs alone.
  - Direct sampling of reservoir fluids

Example: Typical Formation Evaluation for Hydrocarbons

- **Gulf of Mexico clastic reservoir** *(from Castelijns et al., 1999, SPWLA)*
- **Wireline pressures show gas gradient above 300, water gradients below 300**
- **Resistivity high in gas sand, low in water sand, intermediate in shale**
- **Density-neutron logs show gas separation**



Most FE logs are designed for fluid-filled open holes

√ - yes
? - don't know
X - no

	Gamma Ray (U,Th,K)	Spontaneous Potential	Sonic	Density	Neutron (scatter)	Photoelectric Absorption	Neutron Activation (inelastic & capture)	Galvanic Resistivity (laterolog)	Induction Resistivity	Nuclear Magnetic Resonance (NMR)	Dielectric	Electrical Borehole Image	Acoustic Borehole Image	Video Image
Open Hole (fluid filled)	√	√	√	√	√	√	√	√	√	√	√	√	√	?
Open Hole ("air" filled)	√	X	X	√	√	√	√	X	√	√	√	X	X	√
Steel Cased Hole	√	X	X	X	√	X	√	X	X	X	X	X	X	X
Fiberglass Cased Hole	√	X	X	?	√	?	√	X	√	√	√	X	X	X

Recommended Logging Suite for Mars Open-Hole (0.01 atm) Objectives

Priority 1=high 2=med 3=low	Lithology/mineralogy	Depth to bedrock	Physical properties	Water/water ice
Gamma Ray (U,Th,K, no source)	1	1	2	3
Pulsed Neutron Activation (14 MeV inelastic & capture)	1	1	2	1
Aluminum activation (Californium 252 source)	2	3	2	2
Density (gamma-capture w/Pe, Cs-137 source)	1	1	1	2
Neutron (scattering or capture, 241 Am-Be source)	1	1	2	1
Dielectric (typically 30-200 MHz)	1	2	1	1
Induction Resistivity	2	2	2	2
Nuclear Magnetic Resonance (NMR)	2	2	2	2
Video Image	1	1	2	2

Preliminary Logging Suite for Mars Steel Cased-Hole Objectives

Priority 1=high 2=med 3=low	Lithology/mineralogy	Depth to bedrock	Physical properties	Water/water ice
Gamma Ray (U,Th,K, no source)	1	1	2	3
Pulsed Neutron Activation (14 MeV inelastic & capture)	1	1	2	1
Aluminum activation (Californium 252 source)	2	3	2	2
Density (gamma-capture w/Pe, Cs-137 source)	3	3	3	3
Neutron (scattering or capture, 241 Am-Be source)	1	1	2	1

APPENDIX V: ITALIAN PARTICIPATION IN THE MARS EXPLORATION PROGRAM

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ABSTRACT

Recently agreements have been signed between the Italian Space Agency (ASI) and ESA and NASA for the exploration of Mars. These agreements initiate the participation of the Italian scientific community as well as the Italian industrial community in the international program to explore Mars. ASI and NASA have agreed to co-operate in a long-term systematic program of robotic exploration of Mars sustained by a series of missions to Mars in support of their respective strategic goals. The Mars Surveyor Program is a sustained series of missions to Mars, each of which will provide important focused scientific results. ASI is expecting to participate in the future missions with the provision of two sub-system: a subsurface drill and a scientific package. The drill will be capable of drilling and collecting several samples and delivering them to instruments located within a scientific package fixed on a landed platform. ASI is also providing scientific instruments placed on a scientic package (IPSE) fixed with on the lander platform. The goals of the investigations are to study physical and mineralogical properties of bulk soil and dust (atmospheric and surface) as well as geochemical, structural, radiation and geophysical properties of subsurface materials to a depth of 0.5 meters.

INTRODUCTION

The Italian Space Agency (ASI) is a founding member of the International Mars Exploration Working Group, composed of representatives from all space agencies interested in Mars exploration. Recently an agreement was signed between ASI and NASA to facilitate the participation of the Italian scientific community as well as the industrial community in the international program to explore Mars. To date the collaboration has been focused on the NASA Mars Surveyor Program (MSP) lander missions. ASI will provide a deep drill (hereafter called DEEDRI) and a micro-laboratory capable of housing scientific instrumentation (hereafter called IPSE: Italian Package for Scientific Experiments).

In 1998, ASI organised a dedicated meeting in order to involve the interests of the Italian scientific community. During that meeting, a set of instruments was proposed for:

- Atmospheric measurements (1)
- UV luminescence (1)
- IR spectroscopy & mineralogy (1)
- Panoramic spectroscopy (1)
- Ground thermal gradients and conductivity(1)
- Dust flux (1)
- Alpha-Proton-X ray spectroscopy (1)
- Elements abundance (1/2)
- Cathodic-luminescence (2)
- X Diffractometry (2)
- Dust dynamics (2)

With regard to technical maturity, these instruments were classified as either:
(1) based on proven technology ready for 2003;

(2) based on technology requiring further development.
In April 1999, ASI issued an Announcement of Opportunity for scientific payloads to be housed both in DEEDRI or within IPSE for the Mars Sample Return missions MSR 2003-2005. In September 1999, an international workshop was held in Rome for the presentation of the proposals received in response to the AO. The selection of the proposals based on the advice of international referees immediately followed. The guidelines for the selection of the instruments for the Italian package for Mars exploration were based on the 1998 Meeting recommendations and the ESA Exobiology Package. Also the scientific instrumentation expected to be flown onboard other landed missions was considered in order to understand the complementary role that an Italian science package could play and to maximise the scientific return of the missions. Most of the instruments were proposed on the following assumptions:

- the 2003 lander mass budget was ranging between 10 and 12 kg;
- its external envelope was of 450x350x300 cm.

By October 1999, the selected instruments were approved by ASI and presented to NASA. Beginning early in December 1999 the NASA Mars program began a replanning process in response to the loss of the Mars 98 missions. However, ASI continued to support the completions of the Phase A studies for the selected instruments.

DEVELOPMENT STRATEGY OF THE SCIENTIFIC PAYLOAD FOR THE FUTURE MARS MISSION

The experiments selected by ASI to perform investigations on the surface of Mars will be placed on the DEEDRI and on the IPSE sub-systems located on the landed platform. Innovative design approaches that incorporate technological advances in lightweight, high performance instruments were solicited during the selection process. On this basis different experiments were selected.
The design, realization and delivery of these instruments is carried out in the framework of collaborations between ASI, academic institutes and Italian industries. The participation of the academic institutes is significant for the definition of the requirements and for the development till the breadboard phase, with Italian industries having the subsequent major role in realization and delivery of flight models.
The Principal Investigator (hereafter called PI) of each instrument is responsible for the development of the instrument being supported by industrial partners. During the 1st phase of the project the PIs defined the scientific requirements and the instrument general configuration in the framework of the foreseen missions. A preliminary design of the experiment was developed by the reference industry in agreement with the scientific group. This preliminary configuration was reviewed by the PI and the industrial partner in order to identify the feasibility critical items due mainly to:

- the utilisation of new technologies;
- the severe Martian environment (wide temperature range);
- the limited available resources during the mission (mass, volume, power);
- the planetary protection requirements and cross contamination.

The industrial partners undertook a preliminary procurement investigation in order to verify the availability and adequacy of commercial sub-systems and components, identifying which sub-systems had to be designed and developed especially for the project. Analysing the development tests results and the research results, scientific and technical requirements were iterated in order to optimise scientific return with feasibility. This concluded the project phase A. After phase A, the activities will be carried out in a co-operative and complementary way between the PI, supported by their own academic and technical team, and the industrial partner. The responsibilities will be shared in the following manner:

- The PI will be responsible for final instrument specifications especially for concerns related to scientific aspects. The feasibility and the functionality of the instrument will be tested on a Demonstration Model (hereafter called DM) that will be developed by the academic team in collaboration with the industry. Such a model will allow verification of the capacity of the selected instrument configuration to satisfy the scientific requirements and to validate the technological solutions adopted. The PI will have to prepare a preliminary calibration plan and functional test plan applicable on the DM to test it and on the Engineering Model (EM), Qualification Model (QM) and Flight Model (FM).
- The industrial partner will assume the responsibility to define the specifications of the different sub-systems of the instrument. Part of its duties will be to design in detail the configuration of the instrument taking into account the results of the scientific analyses and of the developing test, updating the related analyses and considering all the mission requirements. The industrial partner will identify the different components and those considered as critical, and will generate specifications and select the provider. Using either development breadboards or DM, the industrial partner will test experimentally the critical technologies and realise the instrument.

A very important aspect of the combined activities between PI and industrial partner is the definition of the philosophy for the scientific performances estimation and the calibration processes.
By the end of this so-called B phase, the instrument state of development will be:

- technical and scientific specifications defined;
- DM available;
- complete architectural design with the related analyses available;
- specifications of the critical parts for procurement defined;
- part list complete;
- preliminary calibration plan.

The next phase (C/D) will concern the effective realisation of the following models:

- STM for the thermo-structural qualification;
- EM for the functional verifications;
- QM for the qualification;
- FM for flight.

All the previous activities are developed with ASI financial support. The ASI role during the instrument development is twofold: the ASI Scientific Directorate is in charge of the evaluation of the scientific quality and of the development status of each experiment; also, the ASI technical staff is in charge to evaluate the congruity of the industrial contracts and to define and monitor the different project milestones and the associated deliveries. In the following, we will describe the state of development of some of the instruments proposed for the future Mars missions in the framework of the strategy just described.

DEEDRI

The DEEDRI concept has been developed by Tecnospazio, under direct guidance of ASI, as a multipurpose tool to be used in different space missions. In fact a similar sampler device has been already developed for the lander of the Rosetta mission. The original drill, during the assessment and the Phase A, was modified in order to be used as a real scientific system. In fact, after the selection of the experiments to be housed in the drill, the drill mechanical structure and its electronics were changed accordingly. Moreover it was also foreseen to calibrate the drill torque force in order to use it as a tool to characterise soil mechanical properties. The scientific team, therefore, was also involved in the definition of the new drill configuration.

DEEDRI is a robotic sampling system capable of collecting sub-surface samples to depths ranging from 0.5 to 2 m. The drill unit contains all mechanisms necessary for drilling and collecting samples. As mentioned above, it is devised to permit a gradual increase in performances, with minimum design modifications, allowing the drilling depth to pass from approximately 0.5 meters of the initial configuration to some meters in the subsequent ones. Key elements are the following:

- *mechanical structure*, for structural support, housing and general protection; it contains drill tool as well as translation and rotation group mechanisms;
- *drill tool*, with sampling capability and provision for scientific instruments and local sensors allocation;
- *drill related mechanisms and sensors*: rotation group, translation, translation guides and screw-lead screw mechanism;
- *carousel*, for sample containers accommodation and relevant actuation and control components;
- *loader device*, for sample containers transfer into MAV;
- *TV camera*.

The robotic arm is a manipulator capable of displacing and holding the drill box for the operations (stowage/deployment, Mars surface approach, drilling operations, positioning for delivery of containers to possible return vehicle, positioning for sample delivery to scientific instruments). The drill box contains the key elements to perform the sample collection and distribution operations: the drill rod, the sample containers transfer device and the related mechanisms. The drill will be able to deploy the following sensors: Temperature and thermal diffusivity sensors; radioactivity dosimeters and spectrometers; Resistivity sensors and/or dielectric constant measurements; The drill tip contains a small multispectral camera equipped with a NIR/VIS FPA in order to perform measurements of granulometry and spectroscopy of the different kinds of drilled material. The drill can be used as an experiment to test properties of different materials, if calibrated.

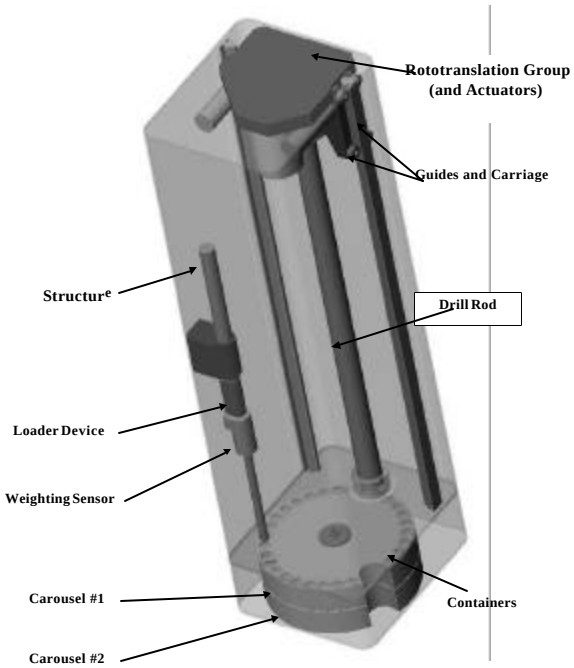


fig. 1 DEEDRI Structure

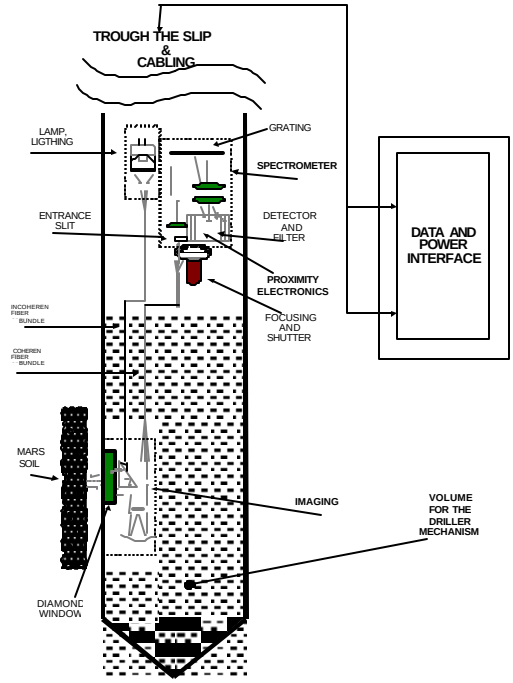


fig. 2 Ma_Miss inside the drill

MA_MISS

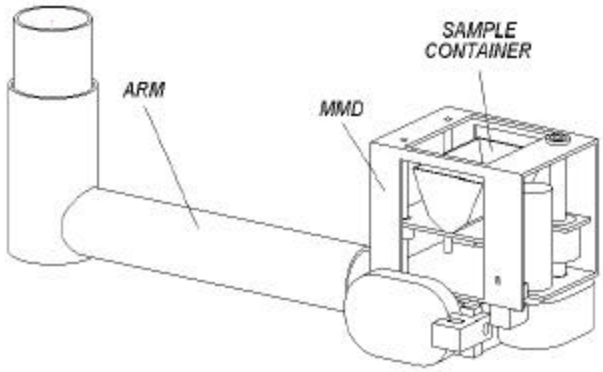
Ma_Miss is a miniaturized imaging spectrometer designed to provide imaging and spectra in VIS/NIR for studies of Martian subsurface layers. The instrument will be integrated into the drill and will be able to provide an image of a "ring", to determine the composition and granularity of different layers, and to identify the mineralogy of individual grains. Ma_Miss main objectives are:

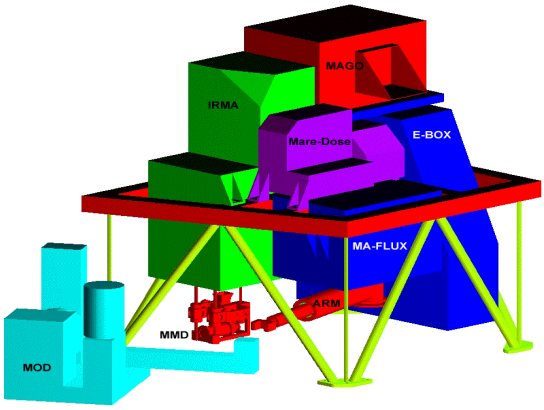
- Image the structure of the column excavated.
- Identify the existence of "lateral anisotropy" on the ring walls.
- Detect the presence of layers containing clays, carbonates and alteration products.
- Identify the grain size distribution and grain structure at different depths along the walls of the hole.
- Study the mineralogy of single grains through their spectrum.

The data are acquired through a flat optical window on the drill wall: through this window the inner surface of the hole is illuminated by a different lamp. The image is acquired by an array of optical fibers simulating a slit. An optical system situated inside the drill will permit to observe details from few tenths of microns to hundreds of microns and to perform low resolution spectroscopy in the selected range. The linear array of optical fibers mimics the slit. The electronics design was focussed on miniaturisation of the electronic components and reduction of harness volume. Having identified the optical fibres as a critical item, a dedicated research has been carried out giving particular attention to the level of space qualification, looking for potential constructors. A preliminary design of the mechanical configuration has been prepared for the architectural verification, taking into account the final part of the drill and the results of the related thermal analysis.

IPSE

IPSE is a scientific autonomous micro-laboratory for Mars soil and environment analysis providing the capability to serve, handle and manage scientific miniaturised instruments accommodated inside its envelope. The IPSE concept has been developed by the CISAS group of the Padua University in strict co-operation with the prime contractor Tecnomare. IPSE is a challenging project in which state of the art solutions were included. Its general configuration is based on a structure with an external envelope to fit within the available room on the lander deck. A small robotic arm is stowed inside the envelope and provides the capability to deliver soil samples to the instruments from the DEEDRI. The first version, now under development, will have basic capabilities but the philosophy of the design is to have a modular system that will evolve with each launch opportunity. Its general configuration for the 2003 MSR mission is based on a structure with an external envelope to fit the available room on the Lander deck and featuring 10 kg mass, inclusive of four scientific instruments described hereafter.





IPSE is designed to operate in Martian environmental conditions and for a lifetime of one Earth year with the aim to

fig. 4 Robotic arm **fig. 3 IPSE Payload accomodation**

be upgraded at each launch opportunity. This means that it will be able to operate at severe temperatures and low pressures in a sandy and windy atmosphere. A modular philosophy has been implemented to allow the maximum level of de-coupling between IPSE and the experiments. It will feature the following main capabilities:

- Autonomous thermal control.
- Electrical interface with the Lander.
- Communication interface with the Lander.
- Control of the robotic arm for sample handling, sample collection from the drill, sample delivery and discharge to scientific instruments.
- Sample preparation prior to analysis. In case of dusty or soft soil samples, the sample will be slightly compressed prior to measurement to reduce it to a proper layer.
- Control of the micromechanisms for sample motions.
- Processing capabilities, including housekeeping functions, scientific measurements scheduling and instruments power on/off, data acquisition, compression, temporary storage and transmission to the Lander.

IRMA (Infra Red Microscope Analysis)

IRMA is a hyper-spectral microscope for the in-situ mineralogical analysis of Martian samples. It works in the 1-5 µm spectral range, with a spectral resolution of 8 nm. Its spatial resolution is 38 µm and the overall field of view is compatible with the sample dimension collected from the DEEDRI drill (12 mm diameter). The investigation carried out by IRMA has the goal to quantitatively characterise the mineral and the micro-physical properties of Martian subsurface samples. The in-situ measurements have the considerable advantage with respect to remote sensing observations of permitting an unprecedented spatial resolution allowing removal of mineral identification ambiguities due to the contamination of the spectroscopic features by the atmospheric gases and aerosols. One of the main tasks of the experiment will be the assessment of the present and past interactions among Martian surface materials, hydrosphere and atmosphere through the study of the mineralogical products of these interactions.

The industrial prime contractor is Officine Galileo, the same as for the ESA-ROSETTA VIRTIS, involved in the project since the beginning. The present plan of development foresees a prototype (breadboard) production in the IAS CNR laboratory for the investigation of the critical parameters (spectrometer temperature, spatial resolution, etc.) and for the spectroscopic analysis of analogs samples of Martian soils. The prime contractor will use the results to modify and optimise the instrument design. The required models are then produced by the prime contractor, while the PI shall retain responsibility over the scientific calibration activity.

MA_FLUX (MArs X FLUorescent Experiment)

MA_FLUX will investigate the Martian surface using the X-ray fluorescence technique, thus allowing the detection of the major and trace chemical elements in the Martian soil, down to a few ppm, using simultaneously the gamma scattering method and the X-ray fluorescence technique. This instrument investigates the interior of samples to a depth ranging between one mm and one cm. Furthermore it defines precisely the X-ray absorption capacity of samples and permits the estimation of the abundance of elements heavier than iron. By analyzing the Compton and Raleigh scattered photons at different energies and at different angles, it will be able to estimate the abundance of the

major elements. By analyzing the hard X-ray fluorescence features, this system should evaluate the chemical composition of the trace elements within a few ppm.

The MA_FLUX instrument is an Italian/French (CNR-IAS, Rome/Institut de Physique du Globe, Paris) co-operation that sees CNR-IAS and CEA/DSM/DAPNIA/Service d'Astrophysique as providing the instrument concept and test, and an industrial part (Laben SpA) that is investigating the thermo-mechanical and electronics design.

MAGO (Martian Atmospheric Grain Observer)

MAGO measures cumulative dust mass flux and dynamical properties of single intercepted particles as a function of time. It allows determination of grain mass, size and shape distribution, and dynamic behaviour of airborne dust. It is a single instrument including three different detection sub-systems (three micro-balances using quartz crystals as detectors of mass deposition, a grain detection system based on the detection of the scattered/reflected light produced by the passage of single grains through a collimated laser light "curtain", and an impact sensor for the detection of the momentum released during the impact of single grains on a sensing aluminium plate). These measurements have never been obtained so far and will greatly improve our capability to interpret and describe processes such as aeolian erosion, redistribution of dust on the surface, transportation and weathering, circulation and climate evolution. The measurements by MAGO have a crucial role also in terms of the identification of hazards for elements sensitive to dust deposition and, in a wider perspective, for the human exploration of Mars. The MAGO sub-systems are similar to or derived from concepts already developed for the GIADA, on board of ESA-ROSETTA, therefore benefit from the development program already carried on for this application.

The MAGO project is an international consortium including Italy (Osservatorio Astronomico di Capodimonte, Istituto Universitario Navale and University "Federico II" in Naples), Spain (Instituto de Astrofisica de Andalucia, Granada) and United Kingdom (University for Space Science of Kent). The hardware development is performed in collaboration with Italian and Spanish industrial partners. Officine Galileo is responsible for the overall management at industrial level.

MARE-DOSE (MArs Radioactivity Experiment-DOSimeter Experiment)

MARE-DOSE is an experiment for monitoring the β and the γ radioactivity during the Earth to Mars cruise phase and at the surface of Mars, in the range 30-300 keV. It consists of lithium-fluoride doped pills which can be exposed to the radiation, reset and readout by heating the pills within a thermo-luminescent process during heating cycle and the emission of an optical signal flux proportional to the absorbed dose.

The DOSE instrument will be realised with a Italian effort of scientific institutes and national space industries. The preliminary phase of design of MARE-DOSE and the subsequent manufacture and tests of the DM are under the responsibility of research institutes (CNR and Perugia University) with the contribution of technical aspects from industry. During the Development Phase the hardware and management activities concerning all the deliverables (will be carried out under industrial control, with researchers retaining control over scientific requirements and performances definition. The test activities on the DM will continue in the research institutes, thus providing useful input for the detailed design of the experiment. This approach will allow considerable reduction of costs, while ensuring that the instrument will meet the scientific requirements imposed during the design phase as well as the overall mission design. At present, the detector has been defined together with the power supply and data acquisition system. A mechanical and optical architectural design has been developed considering the possible locations within IPSE. A model for the thermal analysis has been implemented for the operation phase and for survival during the cruise phase, and a preliminary electronics architecture has been designed.

As a conclusion, it can be said that the effective collaboration between academic institutes and industrial partners for the Mars Exploration program relies on a solid experience previously acquired working on other missions (CASSINI; ROSETTA) and it represents an efficient way to transfer knowledge and know-how between the organisations involved. A detailed description of all the studies carried out during the phase A is provided in the reference.

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Development History of Italian Space Agency *Deedri* Shallow Drill and Associated *IPSE* Science Payload.

During the preparation of 2003 MSR Lander Mission the Italian Scientific Community and by the Italian industry under the guidance of the Italian Space Agency developed an intense activity to participate with NASA to the Mars exploration. When this activity started the Mars Surveyor Program was in good shape, very good results were already achieved by NASA with the success of Mars Pathfinder and a plan was under development for further explorations.

Moreover an effort to establish a strategy for Mars exploration leading to the Mars Sample Return was underway. The ASI scientific top management proposed to the Scientific and Industrial community the possibility play a role in the program that NASA was developing also with a significant French partnership. The idea was firstly presented during a workshop held in September 1998 Pantelleria Island. The response of the Italian planetary science community was extremely positive. The Italian scientist considered the Mars Sample Return (MSR) science objectives appropriate for an extensive and exhaustive study of the origin and evolution of Mars, under many respects, including the evolution of life.

Furthermore, a detailed exploration architecture was developed, also with an ASI contribution. This architectural plan was considered particularly well defined, allowing a progressive series of more sophisticated projects in which both technical and scientific skill could be improved step by step. The Italian Industry showed as well a great interest in the program due to the possibility to use their experience, already acquired participating to ESA, NASA and ASI previous projects.

In this framework an agreement was signed between the Italian Space Agency and the two most important Agencies in the world ESA and NASA for the exploration of Mars. This agreement had the intention to allow the Scientific Italian community as well as the industrial one to participate since the beginning to the International Mars Exploration program. It was considered essential, from ASI side, that the possible technologic contribution to the Mars exploration was accompanied by an equivalent involvement in the development of “state of the art” scientific experiments. Given the previous statements, the Space Science Directorate (Area della Ricerca Scientifica - ARS) of ASI issued the scientific AO the 16th of April 1999, indicating as deadline for the presentation of the proposals to ASI June 15th 1999.

ASI intended to participate to the 2003/2005 missions with the definition of two sub-systems:

- A deep drill (hereafter called **Deedri**);
- A scientific package (hereafter called Italian Package for Scientific Instruments-**IPSE**).

The goal of the ASI announcement was to propose investigations to be carried on the surface of Mars by the MSP 2003 and 2005 Lander Missions. The investigations required instrumentation to be placed on the drill (Deedri) and on a scientific package (Italian Package for Scientific experiments- IPSE) fixed on the lander platform. The goal of the investigation is to study **physical and mineralogical**

properties of bulk soil and dust (**atmospheric** and **surface**), as well as **geochemical, structural, radiation and geophysical properties** of the **subsurface material** up to 0.5 meters.

- The ASI- AO was delivered by April 15th
- The Letter of Intent by the potential Principal Investigators was due by April 25th
- The proposals for DEEDRI and IPSE briefcase were due by June 15th
- 17 LOI were received
- 11 Proposals were submitted

Two international panels were appointed : one for DeeDri and another for IPSE. The two panels rated the experiments on the basis of the following criteria:

- 1.0 -outstanding, must be selected if technically feasible
- 2.0 - very good, should be selected if technically feasible
- 3.0 - sound, may be selected only if mass/volume/power constraints permit
- 4.0 - doubtful, not recommended for selection

The instruments that were rated 1.0 correspond to the so-called "core group" and are extensively described here. The proposals rated 2.0 were considered suitable for a further study, but not to be immediately proposed for the 2003 lander. Both group of proposals as well as the two main subsystem Deedri and IPSE were funded by ASI for ***Assessment and Phase A***.

We include here a table summarizing the mass and power budget of the experiments selected by ASI, as well as a brief description of them. The results of this activity will be also included in the paper that we are writing as our contribution to the "drill Feasibility Paper.

Instruments	Power (watt)	Mass (kg)
Ma_Miss	4	0.84
Irma	13	1.4
Mago	9	1.45
Mare_Dose	15	0.53
Ma_Flux	5	1.35

THE INTERNATIONAL PACKAGE FOR SCIENTIFIC EXPERIMENTS (IPSE) FOR MARS SURVEJOR PROGRAM

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ABSTRACT

IPSE is a micro-laboratory for Mars soil and environment analysis. It provides the capability to serve and handle scientific miniaturised instruments accommodated inside its envelope. The instruments have the goal to perform in situ study of the collected martian samples, thus quantitatively characterising the mineralogy, the composition, the microphysical structure of the materials of the Martian soils down to the depth available to the sampling mechanism. Given the complex structure of the surface material it will be essential to perform in-situ science, both at the surface and at different depths. This is done in order to validate remote sensing observations through specific measurements, identify local characteristics of the selected landing areas, document sample collection both for in situ and sample return. IPSE is an example of a small and flexible lab, that can be integrated on different Landers and Megarovers. IPSE contains:

- Scientific instruments
- A small robotic arm - with five degrees of freedom - to provide samples to the IPSE instruments.
- Power conditioning.
- Electronics for system and thermal control, communications and instrument data handling.

IPSE SCIENCE

The main goals of the future Mars Exploration Programs are related to the open questions on the origin of life, on the preservations of biologic material and human survival. They can be summarized in the following points:

- Determine stratigraphic and structural nature of major crustal units and their spatial/temporal evolution.
- Determine nature and timing of the internal dynamo and resultant magnetic field.
- Determine nature, extent and accessibility of water reservoirs on a global scale
- Demonstrate and employ resources utilization technologies to enable mission activities

Some of the goals are probably accessible in this decade as the improvement of the knowledge of the composition at regional and local level, the identification if and where water is present, the improvement of the knowledge of the local structure and composition of the first layers of Martian soil, where weathering is more pronounced. These scientific goals can be achieved through a combination of orbital science and in-situ science to be performed by a series of missions. The validation of orbital and in-situ science requires *Returned Sample Analyses* and *Subsurface Studies*.

The upper few meters of the surface materials on Mars play a crucial role in its geological history, providing important constraints on questions related to the processes and evolution of Mars. These materials can give information on the processes that are active, the rate of surface modification, the evolution of surface sediments (erosion, transportation, deposition), the relation between sediments and bedrock, the relation between environmental conditions and surface processes. Possibly a blanket 2 km thick, composed of impacts ejecta, may exists, overlying a heavily fractured basement. This layer, megaregolith, could be interbedded with volcanic flows, weathering products and sedimentary deposits. Martian regolith is a product of intensive impact bombardment coupled with volcanic and weathering activity; in the regolith various salts should exist, most likely NaCl brines, forming the so called duricrust. Duricrust is probably composed by fine-grained particles (between 0.1 to 10 μm) taken together by soluble salts or by clorine and sulfur compounds.

All remote sensing spectroscopic observations of the martian surface contain features from the surface material, from the atmospheric gases and from the dust particles dispersed in the martian thus producing mineralogic identification ambiguities atmosphere (Clark et al., 1990). Orbital data can be of difficult interpretation without in situ validation. The in-situ analysis provide a viable solution to remove any mineralogical identification ambiguities due to "contaminating" contributions. The complex structure of the surface material requires to perform in-situ science, both at the surface and at different depths in order to: validate remote sensing observations through specific measurements, identify local characteristics of the selected landing areas, document sample collection both for in situ and sample return.

In the nominal configuration IPSE contains experiments that are suited perform in situ investigation with the following capabilities: imaging and imaging spectroscopy/microscopy (IRMA), elemental analysis and spectroscopy (Ma_Flux), radioactivity measurements (MARE-Dose), dust and deposition phenomena analysis (MAGO), thermal and dielectric properties of the different Martian materials.

Mineralogy Through Spectral Imaging and Spectral Microscopy: IRMA

In the Near and Mid Infrared spectral range (0.8-5 micron) the analysis of the reflectance spectra of planetary surfaces provide essential information to help understanding their composition. IRMA (InfraRed Microscope Analysis) is part of the *in-situ* analysis laboratory IPSE. IRMA shall allow the identification of minerals and shall measure their quantitative abundance on Mars. IRMA is an imaging microscope-spectrometer working on sample provided by the lander sampler, and thus shall not be affected by atmospheric absorptions in the selected spectral range. This represent a considerable advantage respect to remote sensing observations as we shall not require additional modelling of the atmospheric composition for the removal of atmospheric absorption bands. IRMA has the goal to quantitatively characterise the mineralogy and the microphysical structure of the materials of the Martian soils down to the depth available to the sampling mechanism. The instrument will perform *in-situ* microscopic analysis on martian samples which are in all similar to those which will be returned to Earth. Many different scientific issues can be addressed, concerning the present and past conditions and physical processes which have modelled the red planet.

There is an irrefutable evidence for the presence of water ice on Mars; an estimate of the present polar deposits provide a value of about $2x10^6$ km^3 of water ice trapped in the poles (Carr, 1986). In addition there is a growing body of evidence that support an ancient active role for water in determining the present shape of Martian landforms like

valley networks, outflow channels, erosional and fluvial features (Squyres, 1989, Cabrol et al., 1999). However, as the present environmental conditions do not allow presence of stable liquid water on the surface of Mars.
The mineralogy of Martian surface provides a window into physical and chemical weathering processes at work in the present and past Martian environment. Throughout its history, the atmosphere of Mars has been interacting with the surface to alter the pristine igneous material. The interaction on Mars of an atmosphere with the surface rocks and the hydrosphere has led to a wide variety of minerals, such as carbonates, sulfates and nitrates, and clays (ferric oxides and hydrates), that reflect specific processes that have occurred in the past. The mineralogy of these alteration products together with their spatial associations, give then a clue on the environments in which they formed (Calvin, 1998; Catling,1999). The mineralogy of alteration products is an indicator of formation conditions such as oxidation state, abundance and phase of water, atmospheric chemistry and temperature. This knowledge is crucial in understanding the volatile history. Now Mars is a dry planet with a tenuous CO_2 atmosphere. The now apparent missing CO_2 could be in the form of carbonates deposited as chemical sediments or as hydrothermal precipitates. Clathrate hydrates beneath the surface could be an additional reservoir of CO_2. Martian mineralogy on a global scale is dominated by iron spectral features. The presence of well crystalline hematite has been suggested by several investigators and observed spettroscopically both from Earth and spacecraft orbiter. However, there are numerous weathering and thermal alteration pathways that lead to the formation of hematite that may include different past climatic conditions, and so hematite is not a unique indicator of the past Martian weathering history. This may imply that the surface of Mars is anhydrous and/or that formation process were at high enough temperatures to form hematite relative to ferric oxyhydroxide phases. In situ analysis of Mars Pathfinder indicate that poorly crystalline or nanophase ferric-bearing materials dominate at the landing site.
The IRMA observations are characterized by a spatial resolution compatible with direct identification of petrographic textural features. The observed grain size distribution and texture will permit univoque interpretation of the scattering properties of the soil, and the correlation of this information with the spectral measurement will provide quantitative mineral abundances estimate. Microscopic measurements are essential not only as they allow a quantitative abundance determination of the mineral phases but also because the visual characterisation at microscopic level of the samples provide a suite of information on the microphysical properties of the soil (Salisbury and Wald 1992, Crowley, 1986, Mustard and Hayes, 1997). Mineral phases identification, their abundance and their spatial distribution are essential information for understanding their formation and weathering processes. The spectral region between 2.5 and 5 micron is dominated by molecular absorptions caused by vibrational transitions fundamental, by their combinations and their overtones. This region is particularly useful for the determination of carbonates, sulfates, nitrates, water and hydroxyl (OH^-) absorptions in clays (groups of the smectites and scapolites) and other weathering products (palagonites). The region between 1.0 and 2.5 is an intermediate region displaying characteristics bands related to both electronic and vibrational transitions. The region short of 1.1 micron show absorptions related to Fe mineralogy, such as the Fe^{2+} crystal field absorption due to ferromagnesian silicates. On Mars the major contribution is provided by pyroxenes with some olivines around the 1 micron region (Mustard et al. 1990, Soderblom, 1992, Sunshine and Pieters, 1998).
Clays have long been considered likely martian soils constituents as they are typical rock-weathering products on the Earth. Specific strong absorption features of bound water or hydroxyl groups in the 3 micron region has been identified from Earth and from early orbiting S/C (Sinton, 1967). *However, at present there is no specific and univoque identification of clays on the martian surface.* Clays materials have absorption features throughout the range 1.4 – 2.9 micron, either due to bound (adsorbed) water or OH (fig.1). In particular, the 1.4 and 1.9 micron bands are affected by the presence of atmospheric absorption bands and thus they can only be identified by *in situ* measurements. Clay minerals have distinctive features over a wide range of wavelengths from the visible to the mid-infrared. Unfortunately, only few of these features are visible in the martian spectra, thus has been suggested that crystalline clays are not abundant at all on the martian surface, but rather that the surface of Mars is made of amorphous or poorly crystalline minerals such as palagonites or altered volcanic glasses. Palagonites are highly oxidized

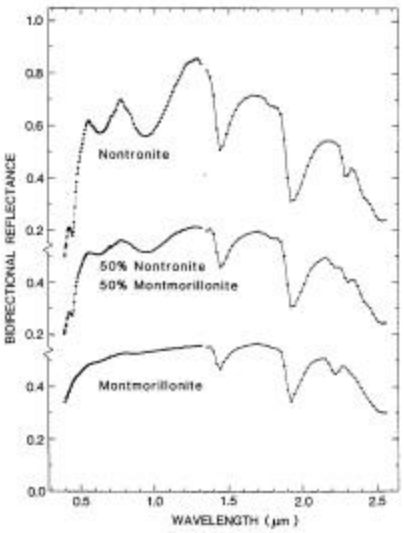


Fig.1: Reflectance of Montomorillonite and Nontronite samples and of their 50/50 mixture. The spectra are offset for clarity.

mineraloids which are composed by complex mixtures of various amorphous silicates, clays, iron oxides, calcite and opal. Characteristics spectral features are located in the region 1.2 through 2.5 micron. Pure carbonates have distinctive absorption features at 2.35, 2.55, 3.4 micron and 4 microns, where very strong bands are observed. They are potential candidates as secondary minerals in the martian soil. Sulfur is present on the martian surface with abundances of about 5 to 10% as reported by Viking measurements. Sulfates show a deep 4.3 micron band, with an extended range ranging from 4.2 o 4.8 micron. In the following are summarised the main scientific goals of the proposed investigation for each sample:

- To provide a full spatial coverage of the specimen at a spatial resolution of 38 µm.
- To describe the physical microstructure of the specimen retrieved by means of visual inspection, and evaluation through appropriate modelling of the scattering properties of the samples grains.
- To statistically evaluate the grain size distribution which in turn is used to quantify the sample texture and material scattering properties. Correlation of this statistical analysis to the reflectance properties of the grains to enhance the scientific information relative to the microstructure of the sample.
- To identify mineral assemblages and their spatial distribution.
- Quantitative determination of relative abundances of identified mineral phases.
- Determination of water abundance in all forms of hydration (adsorbed water, present as interlayer in clays, bound in mineral phases either as H_2O or OH) in the sample.
- Provide a ground truth for remote sensing observations.

The main IRMA characteristics are summarized in the following table:

Spatial Resolution	40 µm (goal: 10 µm)	Size	2 dm^3 volume, ,
Spectral Resolution	10 nm (goal: 5 nm)	Mass	1.4 kg ±20%
Spectral Range	1.0 – 5.0 µm	Power consumption	12 W max
Absolute Accuracy	20 %	Data Volume	30 Mbit overall
Relative Accuracy	1 to 5 % (TBC)	Data rate	Compatible with Lander capability: 10 Mbit/day
Main range of sample reflectivity	10 to 40 %	Allotted time for measurement	Six hours for a complete sample image
SNR at 10% sample reflectivity	>100	Available support from IPSE	Housing, thermal control, power distribution, data handling
Area to be acquired	sample diameter (10 mm)		

Tab. 2: IRMA main characteristics

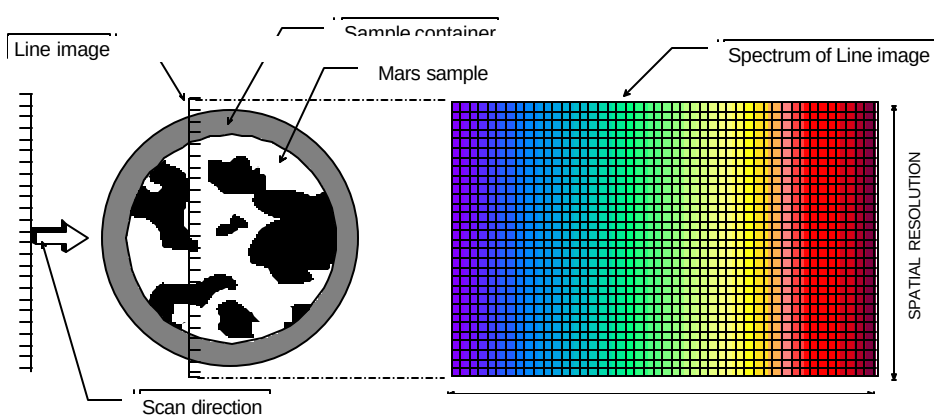


Fig. 2 acquisition scheme

Elemental Analysis: Ma_Flux

The present knowledge of the chemistry and mineralogy of the Martian surface rocks and soils is very limited. The data obtained by the two Viking Landers (6500 km apart from each other) showed a Martian soil chemical composition almost identical, indicating that the lowlands are covered with soil intensely mixed and homogenized by dust storms. However, Phobos-2 infrared and -ray spectrometers found considerable regional variations in surface composition. The goal of Ma_FluX is to detect different elements by means of X ray fluorescence. This tecnique allows to investigate the interior of the samples with a depth of analysis that ranges between one millimeter to one centimeter. The X-ray technique has already been successfully used on board the Rover of the Mars Pathfinder mission. APEX experiments investigates the surface of the samples with a typical depth which ranges only from a few tenths to some

tens of micrometers. Furthermore, the instrumentation defines precisely the X ray absorption capacity of samples and it allows to estimate the abundance of elements heavier than iron.
. The goal is to use a new generation of hard X-ray detectors (Cadmium Telluride - CdTe) to measure the fluorescence lines. The CdTe sensors will improve noticeably the performance of the XRF especially for the detection of heavier elements at hard X-ray energies (from Fe up to U). Together with this experiment, measurements of major chemical elements and characterization of the mineralogy and microphysical structure will be performed by means of MARS-IRMA (InfraRed Microscope Analysis) instrument.
Besides the detection of the major chemical elements (Na, Mg, Al, Si, S, K, Ca, Ti, Fe) to characterize the Martian sample petrography, the possibility to retrieve information on chemical trace elements (K, Rb, Cs, Ba, Sr, Ti, Zr, Rare Earths, U, Th) allows the identification of the differentiation processes during the planet accretion as well as the geodynamical evolution of planetary layers and surface material alteration. Cosmochemical behavior of chemical elements depends on two characteristics. i) The affinity for the major primitive mineral phases which resulted from the thermal evolution of solar nebula; elements known as lithophile (alkaline, earth-alkaline, Rare Earths, U, Th) for their affinity for the silicates phases, elements known as siderophile (Ni, Cr, Co, Pt) for their affinity for metal iron, and elements known as calcophile (As, Cu, Zn, Cd, Pb) for their affinity for sulphur. ii) The volatility which determined their abundance within internal planet; distinction is made as refractory elements (Al, Sc, Ca, Rare Earths, U, Th, Os, Ir, Ru), nonvolatile elements (Mg, Si, Fe, Cr, Ni, Co, Au), volatile elements (Na, K, Rb, As, Ga, Mn, Ge) and very volatile elements (In, Cd, Ti, Pb, Bi). Measurements of the abundance of these elements gives the opportunity for better understanding the pristine nebula composition and environmental conditions during Mars accretion. Trace elements distribution in Martian superficial materials depends on their geochemical behavior:

- during magmatic differentiation processes; partial or complete melting of silicates during the primordial planetary differentiation and further volcanism;
- during secondary processes; metamorphism, chemical and physical alteration and erosion.

Rare Earths are particularly adequate for magmatic processes characterization because of regular decreasing of their incompatibility degree from La up to Lu and because of the sensitivity of Eu and Ce to oxidizing-reductive conditions. Thus Rare Earth can be used to characterize the Martian oxide-reduction state during primordial differentiation. The evaluation of the abundance of elements heavier than iron give access into the field of trace element geochemistry. For each material type, specific trace elements have a larger sensitivity than the major elements and the mineral assemblage to the intensity of the process which has produced or transformed this material. Mars can be considered as a small Earth. Its vicinity to the Earth relative to the Sun allows us to estimate its global chemical composition. Moreover, Mars is geologically less evolved than Earth but its evolution underwent the same basic processes : primordial differentiation (core , mantle), formation of a primitive continental crust. The thermal activity inside the planet has not be sufficient in order to develop plate tectonics but it was efficient enough to produce wide spread volcanism. On the surface the occurrence of liquid water in the past has induced erosion and sedimentation processes.
This geochemical knowledge allows us to estimate *a priori* the abundance level of trace elements in materials present on the Martian surface and to design the instrumentation to measure these abundances. For each material type, specific trace elements have a larger sensitivity than the major elements and the mineral assemblage to the intensity of the process which has produced or transformed this material. This specificity will be involved to make the distinction between samples of the same type : incompatible elements for igneous samples, mobile elements for alteration products. Finally, the possibility to penetrate the sample with γ-rays up to one centimeter is an improvement in order to not affect chemical analyses with sample covered by Martian dust, that already complicated measurements during APXS experiment on Pathfinder. This *in situ* X ray investigation is designed to also provide specific information in order to contribute to the *in situ* sampling strategy and to select among the collected samples those which could be send back to the Earth.

Ma_Flux will investigate the Martian surface using simultaneously the X-ray fluorescence technique and the gamma scattered method. There are three different modes with photons of E< 1.02 MeV may interact with an atom: elastic scattering , inelastic scattering and the photoelectric effect (fluorescence). The technique of X-ray fluorescence involves two principal components: the excitation system and the detection system. In our proposal we intend to use a new kind of hard X-ray detector: the Cadmium Telluride (CdTe). This new generation of detector does not need any cooling and offer a good energy resolution and a good efficiency up to 150 keV, even if it needs thermal stability.Coupled with gamma-ray sources for the excitation system, this instrument should be able to analyze deeply the Martian soil and to evaluate the chemical composition from the Iron up to the Uranium. Using the polycell detectors already developed, will offer a large detection area and, therefore, will give a high sensitivity XRF system.

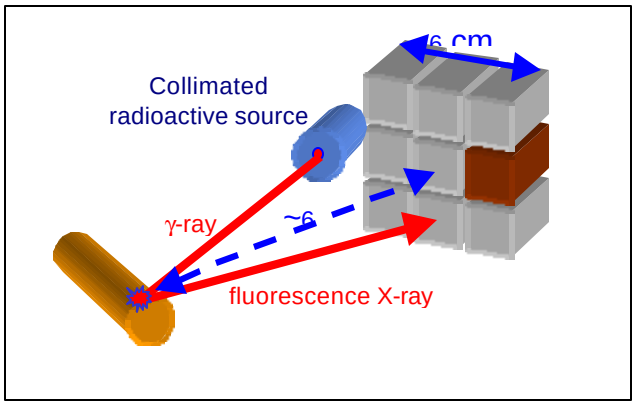


Fig. 3 Detection concept example of a simple CdTe array accommodation

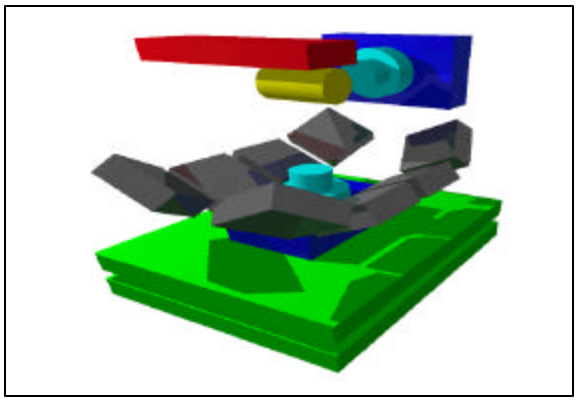


Figura 4 Ma_FluX concept

In addition to that, the imaging capabilities provided by the detector pixelization allows to study the Compton scattering of the γ–ray photons from the source, which in turn, provides the mean density of the irradiated medium. The Ma_Flux instrument foresees 8 of such polycells and two excitation sources ^{241}Am, ^{109}Cd. The two sources will allow to investigate trace elements in the range of Z=37 to 41 (^{109}Cd) and of Z=56 to 60 (^{241}Am) within a few ppm.. The detection area is then composed of 128 independent detectors. The camera present concept is given in the figure above.

Dust Flux Measurements: MAGO

The properties of dust dispersed in the Martian atmosphere, its dynamic structure and evolution and its interaction with gas and surface are among the main items of interest in Mars science. Processes, such as dust storms, dust devils and the dust "cycle" have been identified and studied by past remote and in situ experiments, but little quantitative information is available on these processes, so far. The airborne dust is not a negligible component of atmosphere at all times, it contributes to determine the dynamic and thermodynamic evolution of the atmosphere, including the large scale circulation processes and it impacts on the climate of Mars. Moreover, mechanisms which couple surface and atmospheric evolution, such as aeolian erosion, redistribution of dust on the surface and weathering, are mostly known at a qualitative level. As far as models are concerned, despite complexity, no comprehensive elaboration is capable to represent the variety of phenomena characterising the atmospheric evolution and the dust role. It results that dust on Mars, and in its atmosphere in particular, is a key component, intervening in several evolutionary processes. To measure the amount, mass/size distribution and dynamical properties of solid particles in the atmosphere, as a function of time, is a fundamental step to shade light on the Martian airborne dust evolution, in particular, and on atmospheric processes, more in general. It is evident the need of a step forward in the characterisation of the Mars climate, by the implementation of experiments dedicated to study atmospheric dust, beside the conventional meteorological measurements. The approach and technologies used in the MAGO (Martian Atmospheric Grain Observer) experiment will provide direct quantitative measurements of grain mass, size and shape distributions, as well as dynamic behaviour, a goal that has never been reached so far.
Dust storms are a periodic characteristic of the Martian atmosphere. However, it is nowadays well known that some dust is permanently mixed with the other atmospheric components at all times, even if with variable abundance. Airborne dust contributes to determine the climate of Mars and, probably, it played a role in the past evolution of the climate and the surface characteristics. The dust is relevant in the dynamic and thermodynamic evolution of the atmosphere, including the large scale circulation processes. The amount and distribution of airborne dust affects the thermal structure and circulation of atmosphere on diurnal, seasonal and annual time-scales. The dust dispersed in the atmosphere thermally influences the behaviour of the lower atmosphere, or troposphere (extending up to about 45 km from the ground). Dust blown in the atmosphere absorbs and scatters solar radiation and becomes a relevant thermal source. Several open questions concern the atmospheric evolution, both linked to the gaseous and the solid components. Observations suggest that Mars presents adjacent continents with different thermal characteristics which contribute to drive circulation on regional scales. However, the dust and gas transportation mechanisms are not yet well characterised. The so-called "dust-cycle" is strongly correlated to the seasonal variations of carbon dioxide and water vapour. Atmospheric grains may act as catalysts for the condensation of water and CO_2 in the atmosphere. On the other hand, the surface pressure and the CO_2 variation somehow control the occurrence of dust storms, on both regional and global scales. Last but not least, it looks that dust storms ignition requires a feedback

from atmospheric dust, in terms of dynamics and heating. Aeolian erosion, redistribution of dust on the surface and weathering are mechanisms which couple surface and atmospheric evolution. The exchanges occur in the planetary boundary layer, a turbulent region extending from the surface up to about a few hundred meters. So far, only qualitative information has been achieved on dust injection, transport and removal mechanisms. The mechanisms are driven by the wind intensity and the grain size distribution. Models predict that grains of about 100 μm are raised and blown off (saltation) for friction velocity $u \sim 1.5$ m s^{-1}, while u must be larger than ~ 4 m s^{-1} to lift 1 – 10 μm grains. Actually, the Viking Lander 1 experienced a great dust storm when the measured wind velocities reached some 10 m s^{-1} (at about 1.6 m height). This is compatible with above mentioned u values.

The previous considerations demonstrate that atmospheric dust on Mars intervenes in several atmospheric evolutionary processes. However, the data accumulated so far from remote observations and in situ measurements are rather poor. Mariner 9 observations during the 1971-1972 dust storm were used to derive information about the size distribution of grains, but they cover a limited size range and need further confirmation. Dedicated measurements on Mars Pathfinder gave only qualitative information on the dust coverage with time. Despite complexity, models are affected by several uncertainties, mostly because of the lack of sufficient information coming from observations. These should better constraint the boundary conditions and, then, should render the results more plausible. No comprehensive model is so far capable to represent the variety of phenomena characterising the atmospheric evolution, in general, and the dust in the atmosphere, more in particular.

MAGO is aimed at measuring *the cumulative dust mass flux* and *the dynamical properties of single intercepted particles* and their variations with time. These objectives are in line with the request of environmental measurements about dust and contribute to the definition of the relations between aeolian transport (dust properties and velocity) and atmospheric properties. All these information will significantly contribute to improve the knowledge about the Martian climate. Beside its intrinsic scientific value, MAGO may have various synergistic relations with other experiments aimed at characterising the environment of Mars. As recalled above, the results provided by MAGO on the airborne dust can be related to meteorological data. Moreover, a link can be easily found with experiments aimed at spectroscopic characterisation of surface and atmosphere in different spectral bands. The knowledge of the grain properties, measured by MAGO, is a clue to quantitatively interpret spectroscopic data. Last but not least, MAGO has a role in terms of the identification of hazard conditions for the overall mission. In fact, the data collected about dust flux represent a valuable reference for the safety of other payloads and sub-systems. Actually, MAGO data can be used to identify situations in which the dust amount may become dangerous for the degradation/survival of surfaces/elements particularly sensitive to dust deposition.

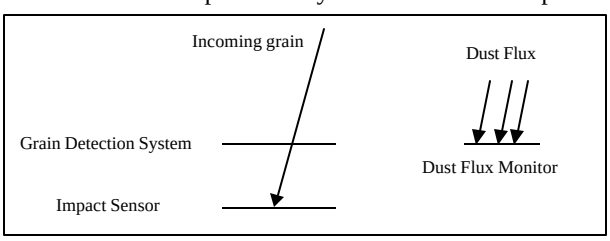


Fig. 5 Sketch of the measurement principle.

The instrument combines three types of sensors, to monitor simultaneously the dust cumulative flux (Micro Balance System, MBS) and the single grain dynamic parameters (Grain Detection System, GDS, + Impact Sensor, IS). The sub-systems are similar to or derived from concepts already developed for the GIADA experiment on board the ESA-ROSETTA space mission. The accumulation of grains on a MBS sensing device allows us to monitor the total mass of grains intercepted by the sensor. From this information, the mass flux of particles as a function of time is derived. This result provides a direct information about the number of particles present in the explored Martian environment vs. time and, thus, about the evolution of dust content, following short and long term modifications of the Martian atmosphere. Three different MBS's, pointing in different directions, are used to investigate directional effects of dust motion. In particular, one of the MBS's points in the zenith direction to measure the flux of grains falling on the surface, an important information related to the transportation and redistribution of dust on the surface.

The determination of the grain dynamical properties (momentum and velocity as a function of grain mass) is obtained by the combined detection of single particles by the GDS + IS sub-systems, working in cascade. The first stage (GDS) measures the velocity of each grain entering the sensitive area of the instrument. The working principle of this sensor is such that it does not perturb the grain dynamics. The momentum of the grain is measured by the second stage (IS), through the impact of the incoming grain on a sensing plate, and the grain mass is derived. Information about the shape and/or size of the passing grain may be derived by the GDS, whose detection signal is related to the scattering/reflection properties of the detected particle. The detection of a large number of events in time allows us to

have a statistical information and to determine velocity/momentum properties vs. mass (and possibly size/shape). The counts of events detected by the GDS+IS system are also a complementary information with respect to the data provided by the MBS sensors. As a baseline, the GDS+IS sensors are pointed in an horizontal fixed direction, as much as possible free from obstruction from other payload/sub-systems. The signals provided by the sensors are directly related to the physical quantities to be measured, so that no complicate computation sequence is needed to extract the scientific data.

Radioactive Measurements: MARE-DOSE

MARE-Dose (MArs Radioactivity Experiment) is an experiment for the measurement of the β and γ radioactivity in space during the cruise to Mars and at the surface of the planet. The measurements will be accomplished by means of a set of dosimeters. The dosimeters will be able to measure the β and γ radiation dose with a responsivity very close to that of a living organism: the experiment is based on thermo-luminescent pills emitting an optical signal proportional to the absorbed dose when heated to a temperature of about 250°C. The set of pills will be used in order to obtain information in different conditions: 1) absorbed dose during one-way cruise from Earth to Mars; 2) absorbed dose in the Martian surface environment.

The challenge of a human mission to Mars requires to consider several aspects of associated risks. One of the hazards that has to be quantified before human exploration of Mars is the radiation dose to which crews will be exposed. Moreover, data for evaluating radioactivity levels at Martian surface are of great interest for environmental studies related to life in general. Because evidences for past climate changes and ancient life, if any, are most likely embedded in soils and rocks, it is very important to perform measurements of radioactivity at different depths under the surface, to monitor the background of the soil/rock and induced radioactivity by interaction with cosmic rays. Crews undertaking the human exploration of Mars will encounter space environment and Martian surface environment, and they will be exposed to ionizing radiation which is damaging for living tissues. Since human tissue is mostly water, the base energy of harmful radiation is defined to be the energy required to ionize water (12.6 eV). Thus, electromagnetic radiation of wavelength 100 nm or shorter can harm tissue; this includes UV radiation, X rays and gamma rays. In addition, high-energy nucleons can interact directly with atomic nuclei in living cells to produce new elements via fission.

Dose will perform measurements of space environment and on Mars surface. The space environment includes all the phases of the mission that are not permanence at Mars surface. During these phases, radiation represents an important and potentially deadly environmental hazard which must be addressed:

- Passages through Earth Radiation Belts (high-energy protons and electrons trapped in the Earth's magnetosphere) will expose craft and crews to severe radiation.
- Galactic cosmic radiation due to highly energetic (up to 1013 MeV) nuclei will be another important source of radiation.
- Solar flares: it appears to involve the liberation of energy stored in magnetic fields.
- Solar particle events (bursts of high-energy particles, mostly protons and alpha particles ejected from the Sun, usually occurring during solar flares) produce X-rays, energetic solar particles and solar plasma.

If radiation hazards have to be kept as low as reasonably achievable, spacecraft and space operations must be designed to minimize exposure to radiation. But the health risk today from radiation exposure on a trip to Mars cannot be calculated with an accuracy greater than perhaps a factor of 10. For that reason, the MARE_DOSE experiment represents a unique opportunity to obtain a direct measurement of the radiation to which crews could be exposed during their permanence in the space environment. The risk associated to radiation while conducting a variety of activities on the surface in space suits or other enclosures (including vehicles) must be addressed by measuring and monitoring the surface and subsurface radioactivity environment. Radioactive sources at the Martian surface are from external and internal origin.

- Solar radiation: based on a simple inverse-square relation, the effect of all forms of solar radiation on Mars should be only 43.3% of that on Earth (at top of the atmosphere) but the influence of the Martian atmosphere has to be studied in detail to determine its shielding properties. The gamma rays contribution of the solar radiation is however very small compared to cosmic sources.
- Galactic cosmic radiation: these particles are modulated by interstellar magnetic fields and by the solar magnetic field; they interact with the molecules and atoms of the Martian atmosphere. In the vicinity of a planet, the flux of the cosmic ray nuclei is modulated by the magnetic field of the planet, if it exists. In the case of Mars, there are

several indications from observations by Phobos 2 and Mars Global Surveyor for a very weak intrinsic magnetic field, not strong enough to deflect charged particles and to produce essential radiation belts. However the Martian atmosphere provides partial shielding. Estimates from R.M. Zubrin et al. (1991), "*Mars direct: a simple, robust and cost effective architecture for the Space Exploration Initiative*". AIAA 91-0326. AIAA 29th) are of 13 rem/yr for Mars at solar minimum (unsheltered conditions), and 6 rem/yr at solar maximum.

- The stochastic solar flares are partially absorbed by the atmosphere of Mars and little actually reaches the surface. Assuming 5g/cm^2 of shielding, estimates indicate 9-11 rem/flare at Mars surface.
- Internal sources An additional radiation flux comes from emissions from within the planetary surface due to the primordial radionuclides ^{40}K, ^{235}U, ^{238}U, 232Th. They contribute to a total of 200 rem/yr to the annual effective dose equivalent from natural sources. The abundance of these radionuclides on Mars has been assessed from that found in the Martian meteorite. Their abundance does not significantly deviate from that of the radionuclides in the oceanic Earth crust.

From these figures, it can be seen that the surface doses on Mars are supposed to be about ten to twenty times higher than those of the worst case at the surface of the Earth. Below the surface, the Martian regolith provides some additional protection against cosmic rays and solar flares to that already provided by the CO_2 atmosphere (ESA Exobiology Science Team Study on The Search for Life on Mars - Final report - June 1998).

The MARE-*DOSE* package that will be used to monitor the β and γ radioactivity emissions, both during the cruise phases and at the Martian surface, is based on doped thermo-luminescent lithium-fluoride detectors. The capacity of these detectors to integrate the energy received from their last reset will be adequately used to measure the collected doses during the different phases of the mission: cruise phase, permanence on Mars. They will be able to measure the β and γ radiation dose received in the range 30–300 keV, with a responsivity close to that of a living organism. The dosimeter is based on thermo-luminescent pills emitting an optical signal proportional to the absorbed dose when heated. The pills are basically constituted by lithium-fluoride doped pills (LiF:Mg,Cu,P) which can be exposed to the radiation, reset and read after heating to a temperature of the order of 300°C. Because the dosimeter can be easily reset by heating, characterization of different environments with the same set of pills is possible.

It could also in principle be possible to monitor the sub-soil radioactivity moving the pills in a drilled hole. Some estimations of the radioactivity level have been made on the basis of the following assumptions: a pill put for one minute in soil with similar concentrations in K, U and Th as Earth oceanic basaltic crust, as expected for Martian crust, would receive a dose of about 200 pGy from the surrounding rock/soil. This value can be considered as a lower value since the contributions due to the penetration of cosmic rays in the sub soil and to the induced radioactivity by spallation are not accounted.

IPSE STRUCTURE

IPSE is a micro-laboratory for Mars soil and environment analysis. It provides the capability to serve and handle scientific miniaturised instruments accommodated inside its envelope. It provides the capability to serve, handle and manage scientific miniaturized instruments accommodated inside its envelope. IPSE is designed to operate in Martian environmental conditions but it could be adapted for other purposes. This means that it will be able to operate at low temperatures and low pressures in a sandy and windy atmosphere. The IPSE structure will contain power conditioning for the various users, and electronics for system and thermal control, and communications and instrument data handling. IPSE is equipped with a processing unit, allowing for a high degree of operational autonomy and flexibility in the operational sessions. A modularity philosophy has been implemented to allow the maximum level of de-coupling between IPSE and the experiments. It will feature the following main capabilities:

- Autonomous thermal control.
- Electrical interface with the Lander to provide and manage power supply to all IPSE subsystems and to the scientific payload.
- Communication interface with the Lander to receive high level commands, telecommands from ground and to transmit the collected scientific data, housekeeping and status parameters.
- Control of the robotic arm for sample handling, sample collection from the drill, sample delivery and discharge to scientific instruments.
- Sample preparation prior to analysis. In case of dusty or soft soil samples, the sample will be slightly compressed prior to measurement to reduce it to a proper layer. This preliminary operation provides a way to evaluate correctly the proper sample position underneath the instruments for optimal focusing.

- Control of the micromechanisms for sample motions parallel (bi-directional micrometric linear motion) and normal to the focal plane for optimal focusing and execution of two dimensional spectral analysis.
- Processing capabilities, including housekeeping functions, scientific measurements scheduling and instruments power on/off, data acquisition, compression, temporary storage and transmission to the Lander.

The IPSE general configuration, for the 2003 MSR mission, is based on a structure with an external envelope to fit the available volume (referred to as "AP Volume 1a") on the Lander deck as sketched in the figure below.
A small robotic arm (SMS) is normally stowed inside the IPSE envelope and provides, during operations, the capability of delivering soil samples to the instruments taken from the deep soil drill (DEEDRI). In the current baseline configuration of IPSE, the Lander Based Sampler (LBS) delivers the samples to be analyzed to the IPSE Sample Management System arm.

Fig. 6: IPSE Accommodation.

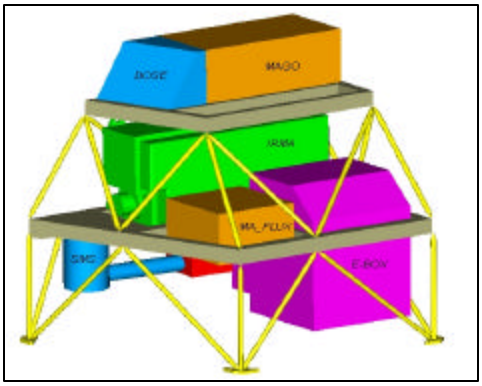
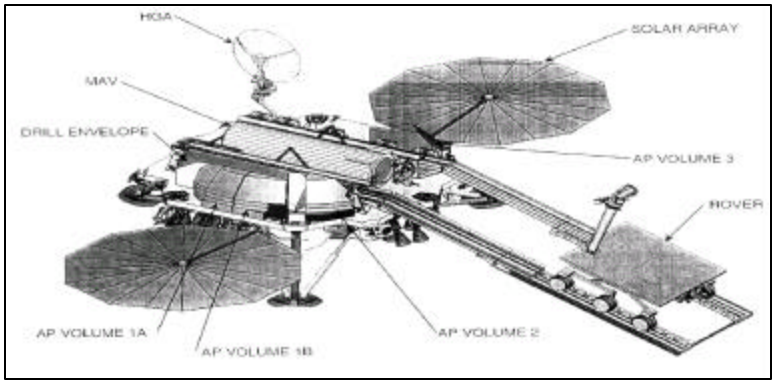


Fig. 7: Lander



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