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Vanguard – a proposed European astrobiology experiment on Mars

A.A. Ellery[1]*, C.S. Cockell[2], H.G.M. Edwards[3], D.L. Dickensheets[4] and C.S. Welch[1]

[1]*School of Engineering, Kingston University, London, UK*
e-mail: a.ellery@kingston.ac.uk, c.s.welch@kingston.ac.uk
[2]*British Antarctic Survey, High Cross, Cambridge, UK*
e-mail: csco@bas.co.uk
[3]*Department of Chemical & Forensic Sciences, University of Bradford, Bradford, UK*
e-mail: h.g.m.edwards@Bradford.ac.uk
[4]*Department of Electrical and Computer Engineering, Montana State University, Bozeman, Montana, USA*
e-mail: davidd@ee.montana.edu

Abstract: We propose a new type of robotic mission for the exploration of Mars. This mission is called Vanguard and represents the fruits of a collaboration that is both international and multi-disciplinary. Vanguard is designed for sub-surface penetration and investigation using remote instruments and unlike previous robotic architectures it offers the opportunity for multiple subsurface site analysis using three moles. The moles increase the probability that a subsurface signature of life can be found and by accomplishing subsurface analysis across a transect, the statistical rigour of Martian scientific exploration would be improved. There is no provision for returning samples to the surface for analysis by a gas-chromatograph/mass-spectrometer (GCMS) – this minimizes the complexity invoked by sophisticated robotic overheads. The primary scientific instruments to be deployed are the Raman spectrometer, infrared spectrometer and laser-induced breakdown spectroscope – the Raman spectrometer in particular is discussed. We concentrate primarily on the scientific rationale for the Vanguard mission proposal. The Vanguard mission proposal represents a logical opportunity for extending European robotic missions to Mars.

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Introduction

Mars exploration has undergone a revival following the fallow years resulting from the Viking mission of 1976. As an astrobiology mission searching for signs of microbial life on Mars the Viking mission was a disappointment to many in the scientific community, yielding at best ambiguous results and at worst, negative results (Levin 1997). The main cause of the new renaissance was the findings of McKay *et al.* (1996) in conjunction with a number of independent biological discoveries concerning extremophilic bacteria. The ALH84001 Mars meteorite was declared as providing possible evidence of former life on Mars (McKay *et al.* 1996; McKay 1997). Despite subsequent doubts concerning the interpretation of the ALH84001 meteorite and the existence of 'nanobacteria' (Folk & Lynch 1997), the shockwave had already rippled through the scientific community. This was also the period of the rise of the Gaia hypothesis which, although not accepted scientifically in its more extreme forms, was implicitly accepted in its more moderate forms (Lovelock 1990). Lovelock's original hypothesis had apparently been shown to be at least partially correct. Indeed, the weak Gaia hypothesis that life forces planetary atmospheres to be maintained at far-from-equilibrium conditions underpins the recent Galileo experiment to detect physical evidence of life on Earth (Sagan *et al.* 1993) and the proposed NASA Terrestrial Planet Finder and ESA Darwin space telescope missions for spectroscopic analysis of terrestrial-type extrasolar planets. However, the planetary-wide spread of a biosphere to maintain such far-from-equilibrium conditions over geological timescales requires the existence of a vertically mediated tectonic recycling process, a condition lacked by all planets in the solar system bar Earth. Perhaps life could exist under more restricted conditions?

For 20 years after the Viking mission, Mars no longer piqued the interest of the scientific community as far as physical exploration was concerned beyond several disastrous missions that graphically illustrate the engineering difficulties in the exploration of Mars. Yet, the legacy of Viking was a rich one, providing the first detailed scientific data on the Martian surface environment; in particular, the highly oxidizing environment of the surface. The discovery that Mars appears to have harboured a much more clement environment in its distant past as demonstrated by water-cut valley networks,

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* Corresponding author.

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channels and flood plains breathed life into the notion that perhaps life on Mars may have existed in earlier epochs when the solar system was younger (Carr 1986, 1987; Jakosky & Jones 1994). It appeared that after the cessation of the heavy bombardment phase 3.8 Gya, Mars is believed to have had a much thicker atmosphere than at present, outgassed from its interior. This may have been >1 bar with a greenhouse effect resulting in surface temperatures high enough to permit the flow of relatively fresh liquid water to survive as demonstrated by palaeolake beds and water-cut channels. The nature of this greenhouse effect is disputed – the relative roles of sulphur dioxide and carbon dioxide in the greenhouse are strongly debated. However, Mars gradually lost the majority of this atmosphere so that by 3 Gya, the pressure had dropped to 100 mbar with temperatures dropping below 0 °C (but still supporting saline liquid water), reaching its present state around 1.5 Gya (these dates are highly uncertain). The liquid water flow on the surface could have been perpetuated for a long period by the flow of increasingly saline brines at temperatures as low as -50 °C, as occurs in the Antarctic Dry Valleys.

At the same time as this model of Martian history was being formulated, the independent terrestrial discoveries of extremophiles inhabiting environments previously thought to be inimicable to life widened the limits of life (Madigan & Marrs 1997). Life, including multi-cellular life, has been found inhabiting deep-sea hydrothermal vents or 'black-smokers' at tectonic margins far beyond the range of sunlight (Corliss *et al.* 1979). These ecosystems are based on chemosynthetic sulphide reduction – this has implications for the Europan environment. Indeed, the bacterial base of this food web in this environment, the hyperthermophiles, are believed, based on RNA studies, to represent an ancient lineage, Archaea, close to the primordial progenitor lifeform on Earth (Woese *et al.* 1990). Such volcanic sub-oceanic environments may have occurred on Mars when it was young. The discovery of bacteria at ~kilometre depths in Columbia River basalts has further widened the conditions thought to be capable of supporting life, though these bacterial populations are limited to 'dwarf' bacteria with suppressed metabolic rates but nonetheless illustrates the possibility of biota deep within the Martian crust (Gold 1992). The discovery of halophilic bacteria in highly saline environments on Earth, which have also been attributed to Mars (and Europa), provides another bolster to the notion of possible Martian life. The discovery of cryptolithotrophic bacteria in Antarctic ice sediments, a cold and dry environment with many similarities to the Martian environment, is particularly important with regard to potential life on Mars. All of these lines of evidence give a real foundation to the possibility that life may have either existed or even perhaps still exists today on Mars. The famous Greenbank–Drake equation characterizing the probability of life and intelligence in our Galaxy, which underpins the SETI (search for extraterrestrial intelligence) programme, was found to be too restrictive in its formulation (Drake & Sagan 1975; Goldsmith & Owen 2001). Life was not necessarily restricted to the so-called habitable zone (Hart 1979). Furthermore, life was not limited to solar energy sources – chemical sources of energy are also viable as the basis for powering metabolism, opening up Europa as a potential site for life. The central tenet became 'follow the water to find life' and indeed, NASA's Mars exploration programme is based around this tenet. Life requires liquid water as the ionizing solvent for biochemical metabolism, and a source of energy of which there are diverse options to power these metabolic processes (Jakosky 1998). These discoveries opened up the possibility of life having emerged on Mars and Europa.

Scientific rationale

It may be suggested that although life has shown itself to be hardy and capable of surviving under the most extreme of conditions, this does not logically imply that life can originate and evolve under such conditions. This is true and is no longer an assumption. Origin of life studies are little more advanced today than the famous Miller–Urey experiment in terms of demonstrating most of the steps leading from the inanimate molecules of life such as amino acids, bases and nucleotides into fully fledged organisms (Miller 1953; Orgel 1994). There exists no well-defined pathway from non-life to life, though there are many theories concerning different stages of it, some of which can be cobbled together to provide a more coherent theory. The Miller–Urey experiment was performed under highly reducing conditions, a condition that is now highly suspect as a model of the Earth's primordial atmosphere. The genetic takeover hypothesis solves the problem of the emergence of self-replication by postulating its origin as clay crystal propagation, with clay minerals acting as catalytic surfaces for polymerization of amino acids and oligonucleotides, though there is no evidence to support this hypothesis (Cairns-Smith 1975). The RNA world hypothesis purports to solve the-protein-or-the-nucleotide problem as RNA can replicate and catalyse organic reactions under certain conditions – so-called ribozymes (Cech 1986; Gilbert 1986). Sophisticated computer modelling which has spurred a whole new development of analysis called artificial life has led to no great insights according to some more traditional biologists, though autocatalytic networks simulated in such work offer an intriguing hypothesis for the origin of genetic information and stable metabolism (Kauffman 1986; Eigen 1971).

Despite our ignorance, however, the fact remains that on Earth, life was very quick to emerge. Fossilized stromatolite deposits from cyanobacterial communities have been discovered dating back to 3.5 Gya (Schopf 1993). Life at this time was already fully organismic – a vast gulf from the current theories of life's origins. Even earlier, life has been implicated by C-13/C-12 isotopic ratio measurements of deposits dating back to 3.85 Gya (Schlidkowski 1988). Although the nature of this postulated life is unknown, it is indicative of metabolism and it is embarrassingly close to the end of the catastrophic bombardment epoch that represented the dregs of the solar system formation process some 3.9 Gya (Cameron 1988). It has even been postulated that life may have arisen earlier only to be eradicated with each catastrophic impact event and then

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re-emerged multiple times (Chyba & Sagan 1992). The origin of life, it seems, is not the result of some random, unusual mechanism, but apparently the result of an as yet unknown deterministic process of chemistry. To suggest an extreme event in the case of the emergence of life on Earth is to contravene the Copernican principle of mediocity (Sagan 1994). The implication is that once conditions allow it, life will emerge very rapidly and spontaneously. This makes the problem of the origin of life all the more frustrating – nature did it in a geological eye-blink, but the human brain has been unable to fathom it. The fact remains however that it did. If life arises wherever conditions are suitable such as on Earth, why not also on Mars when it was more Earth-like? This is the basis of the assumption that life may have evolved on Mars when its environment was more conducive during its early history.

Panspermia theories have been revived of late as a result of the acceptance that meteoritic cross-contamination could occur between terrestrial planets. The suggestion is that life may have originated on Mars and been transported by meteoritic contamination to Earth, or less likely energetically, vice versa – perhaps Mars could have been a 'safe haven' while the more massive Earth was still undergoing catastrophic bombardment events. The evolution of bacterial species such as *Deinococcus radiodurans*, which can survive intense doses of radiation that are more characteristic of Mars than Earth, represents a strange conundrum as there is apparently no evolutionary selection pressure for such capacities on Earth, though the commonest explanation is that this facility evolved to cope with the generation of free radicals or desiccation. The implication is that the discovery of life on Mars, if it were Earth-like and indicative of cross-contamination, would not be the great discovery that life is a universal phenomenon. Although this might be true, the discovery of life on Mars, albeit if found to be related to terrestrial life, would still be a momentous discovery in showing life to be an astronomically important phenomenon. It would yield further insights into the conditions and early evolution of life that cannot be achieved on the Earth, where evidence of life's early events and processes has been all but wiped out through tectonic activity. Such scientific data would be invaluable in tracing our own ancestry.

Thus far, all missions to Mars, both past and planned, have concentrated on exploring the surface. However, the surface is saturated with superoxides and peroxides, which would rapidly degrade any organic material. Indeed, the negative result from Viking's gas chromatograph–mass spectrometer (GCMS) in attempting to detect any organic material was surprising in that organic material was expected to have been delivered from cometary and asteroidal impacts through the aeons. This negative result required an explanation, and experimental simulations suggested that the intense solar ultraviolet (UV) radiation at the Martian surface might produce such highly oxidizing material. This rapidly oxidizes biomolecules to carbon dioxide and unrecognizable residues. The intense solar UV flux is also destructive as it causes mutations in nucleic acids and disrupts proteins and cell membrane lipoproteins. These two factors reduce the possibility of life on the surface itself, although radiation-tolerant bacterial species such as *Deinococcus radiodurans* can survive extreme UV fluxes and organisms protected under soil layers of just a few hundred microns might survive. Beagle2, the only astrobiology-focused mission planned at present, will deploy its robot arm and ground-scuttling mole on the surface and near-surface soil (Sims *et al.* 1999, 2000). The mole will burrow under rocks but not to any significant depth. It is imperative, therefore, if we are to have any reasonable chance of success in detecting evidence of extant or extinct life, that we penetrate beneath the surface of Mars.

Although there have been suggestions that chemolithotrophic microbes might reside at considerable depths ~2–6 km beneath the surface of Mars, such habitats are likely to be closed to robotic explorers for the foreseeable (Ellery 2001). The spatial distribution of chemo-lithotrophs will be somewhat diffuse and heterogeneous, depending on the sources of components of redox pairs, such as sulphides of iron (Russell & Hall 1997, 1999). The Martian geothermal flux is estimated to $\sim 4 \times 10^{-2}$ W m^{-2}, giving a possible depth of liquid water of 2 km at the equator and 5 km at the poles, though localized volcanic activity may have created localized hydrothermal regions at shallower depths, perhaps as shallow as 500 m. Such localized water deposits could persist as liquid for as long as 10–100 Myr. Impact craters would be another possible source of hydrothermal heating (Cabrol *et al.* 2002), particularly at temporary lakes formed from catastrophic outflows which could have persisted for 10 000–100 000 yr. Hydrothermal systems supported by volcanic activity appear to offer the best candidates for supporting a limited ecology (Walter 1996). The energy availability places constraints on the size of any microbial community to an average of ~20 g cm^{-2} over 4 Gyr, suggesting that life on Mars, if it still exists, is sparse. This further suggests that volcanic hydrothermal sites are the most likely concentrations of extant life.

However, our main interest here is in the discovery of fossil evidence for more conventional, photosynthetic forms of life originating from an earlier epoch. The Clifford (1993) model of Martian climatic and hydrological evolution provides the basic framework for our rationale. On early Mars, salts accumulated in ever-shrinking bodies of water as water was gradually lost. These lakes would eventually become hypersaline as in lakes of the Antarctic Dry Valleys, including the Don Juan Pond, which consists of saturated calcium chloride solution that does not freeze until −53 °C. In saline Antarctic soils, water does not freeze at a unique temperature but undergoes a phase change so that some liquid can exist at −70 °C, and viable but dormant bacteria can survive as has been found in the Don Juan Pond at −50 °C (Anderson & Tice 1989). The concurrent effects of the elevated melting point of hypersaline brines and the potential 'water greenhouse' effect of high relative humidity localized in channels (Pathare & Paige 1996) indicate that emerging brine water, even if temporary, could flow over the surface. This is consistent with the hypersaline brines postulated from Mars Orbiter laser altimetry (MOLA) data (Lobitz *et al.* 2001). As water receded further, any indigenous surface life that may have existed on early Mars

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would have retreated below ground into porous rock as endoliths and deep subsurface sediments as chemolithotrophs during surface desiccation and freezing. Some populations may still be preserved freeze-dried in a dormant state in permafrost. We are concentrating on the detection of biomolecules from former microbial biofilms, now buried and preserved in the near subsurface of former palaeolakes or other ancient water bodies on Mars. There are sound biological reasons for believing that early Earth-like Martian conditions would generate a strong selection pressure for the evolution of photosythetic energy capture despite the Sun having been some 25–30% dimmer some 4.0 Gya. The Sun, even at such a reduced energy output at Mars orbit, represents the most bountiful source of energy available for metabolic activity. We therefore hypothesize that on the expansion of life into illuminated surface habitats on early Mars, the selective pressure of solar radiation availability would have driven the original microbiota to evolve photosynthetic pigments to harness this ubiquitous energy and to develop energy-efficient photosynthesis, and consequently the evolution of UV-protective and photosythetic pigments. It is suggested that large populations of photosynthetic cyanobacteria were already widespread on Earth some 3.5 Gya, though this is currently contested (Schopf 1993). The Martian biota would also have required protective pigments against UV radiation damage to vital molecules such as nucleic acids and proteins, assuming that they were based on a similar biochemistry. If this is correct, the occurrence and spatial distribution of preserved pigments or their derivatives in the near subsurface profile beneath the oxidized zone would offer a detectable source of data on former life on Mars. Thus, fossil evidence of such lifeforms might be detectable in the form of decay products from photosynthetic pigments that might survive in the Martian soil below the oxidizing layer. Such pigments should be detectable *in situ* by non-destructive laser Raman spectroscopy, as on Earth. Just how deep the oxidizing layer on Mars extends is unknown. A number of suggestions have ranged from 1 to 3 m or more with 2 m being a common assumption (Zent & McKay 1994; Patel *et al.* 2002, private communication). Until we attempt to measure its depth, this lack of knowledge will act as a considerable stumbling block in attempting to formulate models of habitats of former or even extant life if it exists at depth. Given this lack of sub-surface data, there is thus a need to generate multi-variate data on the vertical profile of the Martian sub-surface. Microbial communities which migrate towards the surface to exploit light will be restricted to the focused zones penetrated by photosynthetically active radiation (PAR) and UV radiation. The result of a uniform source of solar radiation is a laterally homogeneous stratified biofilm, influenced by the seasons. This biofilm typically contains high concentrations of photosynthetic and UV-protective pigments with distinctive functional molecular structures. Hopanoid derivatives from cell membranes have been identified from relic cyanobacteria 2.5 Gya on Earth (Summons *et al.* 1999). At this time, there would still have been liquid water on Mars, indicating the viability of detecting such ancient deposits. For these evolutionary and practical reasons, Wynn-Williams & Edwards (2000) favour shallow searches for the remains of photosynthetic bacterial and cyanobacterial communities rather than deep drilling for chemolithotrophic bacteria.

There are several possible locations for former or even extant life on Mars. First, regions where water existed for significant periods of time such as palaeolakes and water-cut channels (Doran *et al.* 1998). It appears that there is also evidence of recent water flows in gulleys on the cold, shaded sides of slopes such as that at the Noachis Crater (Malin & Edgett 2000), but these are likely to be inaccessible to near-term robotics missions. Secondly, hypersaline brines (Wynn-Williams *et al.* 2001), as found in Antarctic Dry Valley lakes, or evaporite deposits indicative of salt mineral deposition in water are another option. Thirdly, deposits associated with hydrothermal vents powered by volcanic activity were mentioned earlier. Finally, the permafrost–water interface may potentially harbour life (Vorobyova *et al.* 1997). The Mars Global Surveyor in orbit around Mars has been an unprecedented success. Its imager has recently discovered evidence of ancient lakes with layering features indicative of erosion and sedimentary deposition owing to the action of water. One productive region for the search for preserved biomolecules would be in the dry bed of one of the ancient lakes of the northern hemisphere such as the recently discovered regions of sedimentary layering. The Crater Gale of 170 km in diameter and 3–4 km in depth shows a series of layers up the crater's central mound. The layering is characteristic of water sedimentation and would have required several million years to form. Wynn-Williams (2001, private communication) favoured either the lakebed of the Gusev crater at 14° S 184° W or the Ma'adim Vallis riverbed. Ma'adim Vallis is believed to have originated from hydrothermal melting of permafrost some 0.7–2.0 Gya. The 166 km diameter Gusev crater is believed to have been an ancient ice-covered lake that existed prior to the carving out of the Ma'adim Valley which was subsequently flooded by the Ma'adim Vallis outflow. Stromatolite deposits (if they exist) may be concentrated at lake edges if terrestrial deposits are taken as the norm. However, given that Martian craters are generally shallow, such as the Newton crater and Gale crater, this may not be the case, making the accuracy of landing less critical (Parnell 2002, private communication).

The search for biomarkers

There are a number of approaches to the astrobiological study of Mars. Reliance on the investigation of Martian meteorites alone is unreliable as the sole source of astrobiological data owing to the rapidity of terrestrial contamination once they have landed. Another approach is sample return. Such a mission would typically acquire a small sample of Martian soil and/or rock robotically and return it to Earth. The advantages of this approach are that it provides a means for human scientists to study the sample directly in a laboratory. The disadvantages of sample return are that it is unknown how biomarkers and other chemical evidence might be altered by

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the sterilization/quarantine process and the limited sample size. A third approach is to study samples *in situ* by robotic means. The advantages of this approach are that it potentially affords the opportunity to study a greater sample size and to investigate undisturbed signatures *in situ*. It has the disadvantage that it relies on robotic detection of life, which in some respects is less powerful than human examination coupled with instrumentation on Earth.

Presented here is the Vanguard Mars mission proposal as a logical successor to the UK-led Beagle2 mission due to fly to Mars in 2003 on the European Space Agency's (ESA) Mars Express bus (Ellery & Wynn-Williams 2002). Beagle2 is a major contribution to the UK astrobiology effort (Cowan *et al*. 1999). Although the financial support for ESA's proposed Aurora programme of planetary exploration is doubtful, it is considered that the science community will support the authors in the contention that Mars exploration should be a high priority for ESA and that ESA should capitalize on the momentum provided by Beagle2. The original suggested launch window was 2007, but that looks highly unlikely. Given the BepiColumbo mission is likely to fly in 2009, the earliest launch opportunity is 2011, almost a decade from now. The Vanguard mission proposal presented here represents an ongoing pre-phase A conceptual study. It is important to note that Vanguard, although primarily an astrobiology-focused mission, is not exclusively such. The instrumentation to be deployed will be used to provide much-sought geochemical/geological data on the Martian environment. The alpha–proton–X-ray spectrometer (APXS), which was the prime instrument onboard the Pathfinder rover Sojournor and is the prime Athena instrument onboard the planned Mars Exploration Rover (MER), is limited to determining the concentration of the elements of the rock and soil. It cannot provide data on the mineralogy of the rock or soil, which must be inferred through rock models. Thus, there is a specific need for mineralogical data on the Martian geology, yet no mission is currently planned to provide this much-desired data (the mineralogical Raman spectrometer that was originally planned for the Athena payload on the US Mars Exploration Rovers was dropped).

The next question concerns biomarkers that may be exploited in the search for life. Bacterial morphological fossils are unlikely to be found as they do not fossilize readily and morphology alone is ambiguous, but fossil evidence of the existence of bacterial communities such as stromatolite deposits would provide a biomarker. The problem with determining biomarkers was highlighted by the ambiguous Viking experiments, which were based on attempting to measure evolved gases from respiration. The approach used on Viking was to radioactively tag nutrients and measure their uptake by soil cultures maintained under ambient conditions, but the results were inconclusive – they took no account of more recent discoveries in chemolithotrophic metabolism. The lack of organic materials detected by the Viking GCMS imposed the final decision. Furthermore, such techniques require significant volumes. These techniques made tacit assumptions that can lead to erroneous or ambiguous results. The fewer the assumptions made, the more secure and unambiguous the results are. One of the most basic assumptions is that life will be based on CHONPS elements. There are sound cosmological and biochemical reasons for this (Barrow & Tipler 1986). Hydrocarbons, especially aromatic compounds exemplified by polycyclic aromatic hydrocarbons (PAHs), are the dominant organic species found in extraterrestrial sources so cannot be used as biomarkers. High concentrations of SO_x, NO_x, H_2S, NH_4, CH_4, PO_4, alcohols and amino acids are strong indicators of prebiotic processes. Reduced forms of Na, Fe, Mg and Mn, which act as catalysts in metabolic reactions, may provide indications of life. Sulphur deposits might be indicative of sulphate reduction metabolism. However, these chemical species can be formed by abiotic geochemical processes. Isotopic ratio measurements can differentiate between biogenic and non-biogenic origins. Carbon isotope ratios C-13/C-12 favouring C-12 are indicative of biochemical activity. A high H/D ratio might also indicate deuterium depletion indicative of metabolism. However, isotopic ratio measurements alone are unreliable as biogenic processes can yield a variable isotopic signature and can often be replicated under certain abiotic conditions. Furthermore, the measurement of isotope ratios requires the robotic extraction of samples with isotopic ratio analysis, which imposes further complexity on such missions.

As amino acids are found in interstellar dust clouds and meteorites, amino acids themselves do not indicate biogenic activity unless they are found in chiral mixtures. Chirality is generally considered to be indicative of extant life only – chiral mixtures quickly become racemic due to natural diffusion with the outside environment. However, the analysis of chiral activity requires extraction and mixing with chiral reagents, invoking loss of spatial information and the addition of technological problems, albeit not insurmountable adenosine triphosphate (ATP) is the universal energy storage molecule for life on Earth, though it is likely that ATP was preceded by a simpler precursor molecule in the early stages of life. ATP levels are directly related to metabolic rates, so bacteria existing under starvation conditions such as expected at depth – so-called dwarfism – are unlikely to provide a strong signature. Furthermore, ATP degrades rapidly after death so would be useless as a biomarker for microfossils. However, ATP measurements can be used to detect living organisms in a thriving ecology. We are concerned with fossilized evidence of former life as the most likely scenario on Mars.

Macromolecules such as kerogen, oligonucleotides or hopanoids would offer evidence of biogenic processes – this may be construed as anthropocentric but we have no evidence of other types of life, so the principle of Occam's razor forces us to restrict our definitions of life and its nature. Whilst being inclusive for our quest for any biomolecules and inorganic patterns left by former life (Friedmann & Weed 1987), we are focusing our attention on pigments because they are vital to the survival of any surface microbiota on a terrestrial planet in the solar system and they would have evolved in some form if life itself arose at all. There is therefore the need for an instrument to characterize *in situ* the microstructure and

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inorganic composition of potential microbial habitats on Mars with concurrent analysis for molecular components of organic material and unequivocal evidence of biomolecules, without any preparation or prior identification of compounds. Specific requirements include:

- non-intrusive *in situ* analysis of the microstructure and inorganic composition of potential microhabitats for microbial life;
- non-selective analysis of organic compounds in near-surface substrata below the oxidized regolith zone, without any extraction or preparation;
- diagnosis of biomolecules from their functional components (e.g. rings and isoprenoid units), without prior knowledge of the identity of compounds;
- diagnosis of focused strata of biomolecules (e.g. light-constrained pigments in the profile of palaeolake sediments) in spatially dispersed cores/samples to minimize the chance factor of heterogeneity;
- emphasis on the ecological function of component parts (e.g. UV-absorbing rings for former surface microbial survival) in environmentally challenging conditions;
- a database of terrestrial microbial biomolecules (especially photosynthetic and photoprotective pigments from potentially analogous primitive microbes on Earth), e.g. photosynthetic bacteria and cyanobacteria;
- confocal microscopic imagery of the habitat structure and any fossil or preserved microbes.

The Vanguard mission scientific instruments

Raman spectroscopy meets these needs as it depends on the scattering of laser radiation at a wavelength shifted from that of the incident light by its interaction with the molecular vibrations and rotations in the constituents of an untreated sample. Raman spectroscopy is a laser-based technique that can be used to detect organic and inorganic compounds *in situ* by detection of scattered light. A Raman spectrometer determines the vibrational signature of molecules arising from inelastic collisions between the photons of the exciting laser source and the component parts of the target molecule. A small proportion ($\sim 10^{-5}\%$) of the incident photons are scattered with different wavelengths and intensities due to inelastic Raman scattering, which are collected by the excitation optics for subsequent analysis. The vast majority of the scattered light is unchanged in frequency due to elastic Rayleigh scattering, which can be filtered out and normalized to zero. Raman spectroscopy provides for any compound a unique 'fingerprint' of all its components, which can often be detected in a mixed biomolecular pool of a cell or natural community. Corroborative groups of bands in this spectrum can thus be used to identify the compound in a mixed sample. Its water signature is small so that it is applicable to untreated field-fresh material (the search for water would require augmentation with an infrared (IR) spectrometer). Near-IR (1064 nm) excitation is optimal for minimal interference by autofluorescence of pigments, but typically requires an interferometer to analyse the spectra (Edwards & Newton 1999). A compromise with an 852 nm laser (giving some autofluorescence) permits miniaturization with a charge-coupled device (CCD) detector – the Confocal Microscope and Raman Spectrometer (CmaRS; Dickensheets & Kino 1998; Dickensheets *et al.* 2000). The CMaRS micro-Raman spectrometer is composed of two main parts: a lightweight spectrometer, 852 nm diode laser source and control electronics housed within an electronics compartment; and a compact probe (connected to the instrument by fibre-optic coupling) incorporating the confocal microscope and Raman filters. However, the development of IR-sensitive InGaAs detectors now permits the miniaturization of Raman spectrometers for fieldwork and planetary missions whilst retaining the optimal 1064 nm laser wavelength (Wynn-Williams *et al.* 2002). By definition, the proposed near-surface location of pigment molecules makes analysing them by a non-intrusive system such as Raman spectroscopy technologically feasible. Their distinctive Raman spectra adds to their suitability as biomarkers – a laser-Raman spectral database is being accumulated at the University of Bradford for recalcitrant derivatives (such as fossil porphyrins and isoprenoids) of key pigments such as chlorophyll and caretenoids. Furthermore, between wavenumbers of 500 and 100 cm^{-1}, there are frequently inorganic bands that are valuable for determining the mineral compositions of the underlying substrate – quartz, silica and iron oxides. The miniature infrared laser Raman spectrometer has the concurrent potential for scanning confocal microscopy of the strata and biomolecular debris, together with IR spectroscopy for water, with the same optics (Dickensheets 2001, private communication). The combination of these corroborative analyses will help to provide unequivocal evidence of former life on Mars. Furthermore, it has been suggested that Raman spectroscopy may provide the means for fluid-inclusion analysis (Parnell *et al.* 2002).

The primary instrumentation to be deployed by the Vanguard mission proposal are the Raman spectrometer, the infrared spectrometer and, more provisionally, the laser-induced breakdown spectroscope (LIBS). The LIBS instrument fires a pulsed laser beam at its target that vaporizes a small portion of the sample into plasma. The spectrum of the plasma may be analysed to provide elemental geochemical analysis similar to the APXS that was flown on Sojournor. These instruments represent state-of-the-art instrument technology (primarily in the US) and provide the means to extract precisely the scientific data on geochemistry and astrobiology that will enhance our understanding of the Martian environment dramatically. These represent the major instruments for Vanguard – other instruments that must be included are a small meteorology package, a small environment package and a seismometer (the implementation of a neutron spectrometer and ground-penetrating radar is being investigated), but these are yet to be defined. This instrument suite can provide a diverse set of scientific data. It is proposed rather unusually that Vanguard be a European mission flying almost exclusively American instruments. It is envisaged that the US CMaRS micro-Raman spectrometer/imager could fly on Vanguard – it may undergo trials in Antarctica in the near future with the British Antarctic Survey (Dickensheets *et al.* 2000). Deposits of biofilm typically

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contain high concentrations of photosynthetic and UV-protective pigments with distinctive functional molecular structures. Their component parts generate distinctive Raman spectra, independent of their hydration state. Experience with microbial communities in extreme Antarctic desert habitats analogous to those of early Mars shows that these key biomolecules can be detected *in situ* within the biochemical pool of mixed populations (Edwards *et al.* 1999). The overall Raman spectrum not only reveals organic matter and the composition of its mineral substratum, but also reveals the nature of biomolecules present and their potential function (such as UV absorption).

An important contributor to the quality of the scientific data, apart from the design of the instruments themselves, is the selection of the sites for deployment of those instruments. Traditionally, the robotic deployment of instruments is not defined as part of the instrumentation, yet it fundamentally defines the quality of the data acquired (Ellery 2000). The first requirement was for multiple deployment sites – unique datasets are valueless in traditional science, so the requirement for replicability was considered to be essential. Certainly, a statistically valid spread of data cannot practically be achieved in exploratory planetary missions. We determined that three sub-surface targets were practical, which should be selected on landing across a 1 km transect of a sedimentary basin. This essentially defined the robotic requirements for the mission.

The Vanguard mission surface package

The major design constraint was that the Vanguard lander mission must be accommodated by the Mars Express-class spacecraft bus that will carry Beagle2 to Mars orbit in 2003. It is a pre-existing bus with a well-defined payload capacity. The Mars Express mission in 2003 has a payload capacity of 176 kg of which 60 kg comprises the Beagle2 lander. The delivered mass to the Martian surface is the Beagle2 lander of 30 kg, the rest comprising the entry, descent and landing system (EDLS). In considering the requirements for Vanguard's robotic infrastructure, this was not sufficient. A mass limitation of 100 kg was imposed (including the EDLS) – an increase of just over 50 % on Beagle2. This would mean limiting the orbiter instrumentation to 76 kg; i.e. not significantly under half of the total Mars Express payload capacity. This was considered acceptable as the Vanguard mission is being proposed as the primary instrument package, rather than as a subsequent afterthought in the primary instrument package as was the case with Beagle2 in the Mars Express payload manifest.

The requirements of the mission required a 48 kg surface package including some form of mobility system to range across the surface and some form of surface penetration mechanism. The approach selected was that which maximized the scientific return, maximized the use of demonstrated technology and minimized complexity. Vanguard comprises a minimal base station lander to provide relay communications to the Mars Express orbiter, a single 14 kg free-ranging microrover similar to Sojournor for mobility (named Endurance after the explorer Shackleton's ship), and three ground-penetrating percussion-based moles similar to the PLUTO (PlaneTary Underground TOol) to be deployed by Beagle2 (named Orpheus 1, 2 and 3 after the mythical Greek lyre-playing venturer into the underworld). The microrover concept has already been flight-tested through Sojournor and the valuable lessons learned can be implemented on Endurance (Miller *et al.* 1989; Wilcox *et al.* 1992; Miller & Varsi 1993; Matijevic 1998; Morrison & Nguyen 1998) (Fig. 1). One of the authors (Ellery) is currently investigating a novel mobility/suspension system for the microrover to provide robust traversal over the Martian surface within the requirements for low mass, complexity and power consumption. The PLUTO mole is currently under development at DLR in Germany for flight on the Beagle2 Mars lander (Richter 2002, private communication). The lander allows mounting of the static meteorological, environmental and seismometer instrument packages, while the rover carries the Raman spectrometer, the infrared spectrometer, the (provisionally) LIBS and more speculatively a ground-penetrating radar. The Raman sensor head can readily be incorporated into the mole (Richter *et al.* 2001). The LIBS, like the Raman spectrometer, generates a reading rapidly without the long integration times associated with the APXS. Furthermore, the LIBS can be integrated readily with the Raman spectrometer using the same fibre-optic coupling (Bertrand 2002, private communication). The moles would be mounted into a vertical configuration on the microrover, and each would carry sensor heads to the instruments mounted on the rover coupled by dedicated optical-fibre-carrying tethers. Each mole would be deployed independently by the rover at three different sites. Each mole would penetrate the surface delivering the instrument sensor head to the sub-surface environment. The maximum penetration depth was provisionally set at 5 m – regrettably, so little is known of the sub-surface environment of Mars, that this depth was imposed on the basis of guesstimation tempered with practicality. The percussion system of the mole provides a well-defined stimulus source for the lander seismometer to enable local geophysical data to be obtained. The LIBS is a more recent addition to the payload manifest, so its deployment has not yet been defined. It could certainly be deployed on the rover for surface exploration, perhaps while the rover is stationary during mole deployment. It is not yet clear whether it could be deployed by the mole without increasing the complexity of the mole's depth profile and corrupting the pristine borehole environment. To minimize Vanguard's robotic complexity, each mole undergoes a one-way trip – down – with no provision for recovery or for returning samples to the surface. A gas-chromatograph/mass-spectrometer, which is typically massive and power-hungry, was not included for this reason. Perhaps, some future Vanguard 2 might implement such instrumentation to provide analysis of depth-recovered soil samples and all the inherent complexities that would incur, but the need for simplicity was considered paramount for Vanguard. On completion of the mole's maximum depth of penetration, the tether is severed and the Endurance rover moves on to the next selected site

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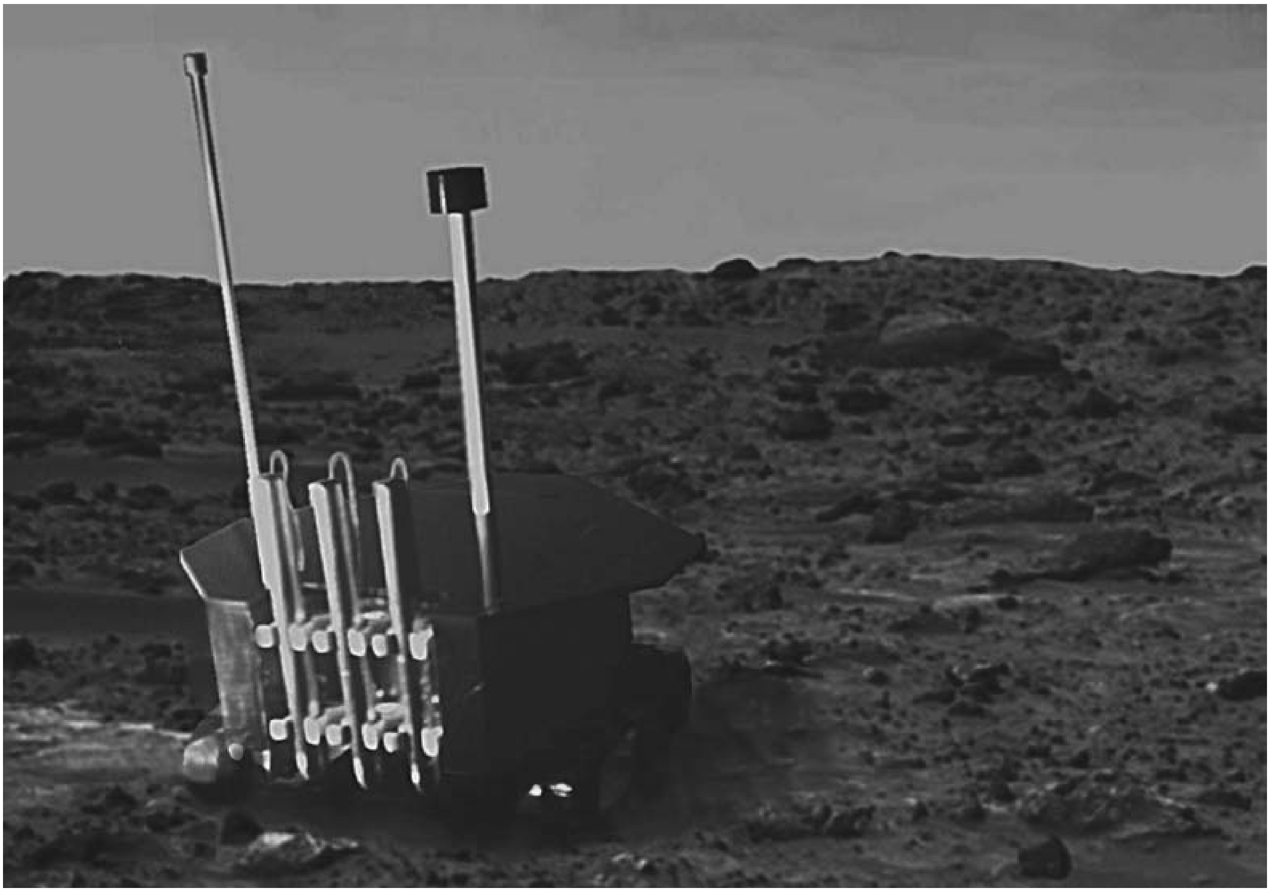

Fig. 1. Artist's impression of the Vanguard microrover (Endurance) deployed on the Martian surface (courtesy of Ashley Green).

for deployment of the rest of the moles, each in turn. The one-way trip eliminates the need to design the tether to undergo tensioning, eliminates the need for consideration of hole integrity, and the implementation of hole casing eliminates the need for complex recovery mechanisms such as re-spooling of the tether and coordinated back-driving of the mole, eliminates the need for consideration of re-mounting the mole in a launch tube, and eliminates the need for complex sampling tools. This one-way trip imposes a requirement for an 'astrobiology expert system' onboard the rover to perform quick-look analysis of the data, and on the basis of that, determine whether further detailed analysis is required – although perhaps not strictly necessary, this was considered a highly desirable value-added capability. This would minimize the chance of missing interesting phenomena during the mole's descent into the sub-surface. The Vanguard mission thus represents a true 'robotic astrobiologist'. The separation of the instruments and the incorporation of the sensor head into the mole offers a versatile solution to the problem of obtaining scientific data from difficult-to-access sites. We envisage that a similar type of approach may be adopted for the exploration of the sub-surface of Europa.

Conclusion

The Vanguard architecture represents a considerable engineering challenge with a high scientific capacity. It purports to offer the maximum scientific return within an achievable engineering package – an optimal architecture. We are not aware of any similar type of Mars mission being proposed in Europe, USA or elsewhere at the present time. We suggest that the Vanguard mission offers a rich return in scientific data in a small mass package that cannot be equalled. Furthermore, it represents a fitting successor to the innovative Beagle2 mission, which will be essential if Europe and the UK, in particular, is to maintain its strong role in Mars exploration.

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