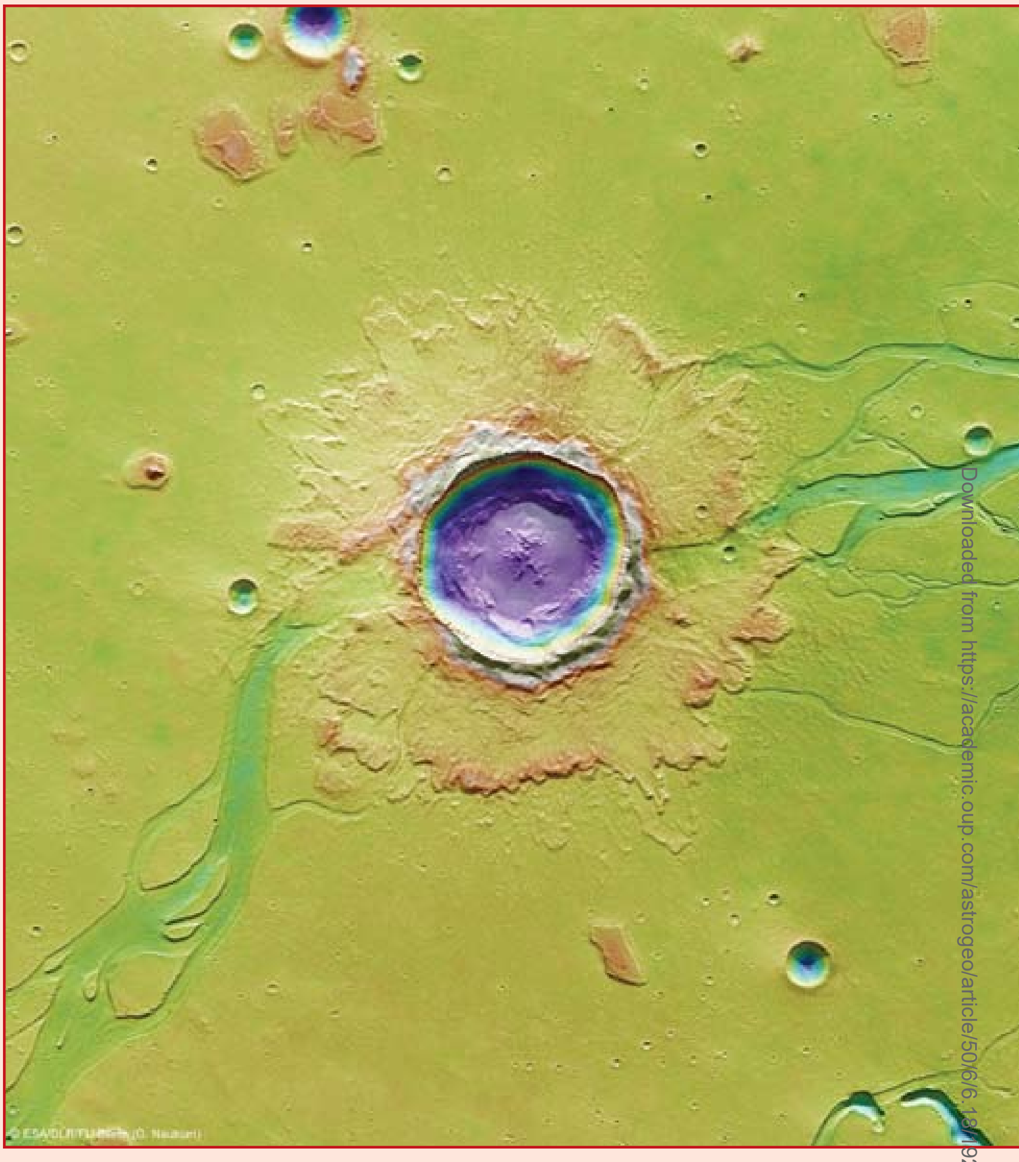
Where to land on Mars



In June 2009 a community workshop discussed what priorities in landing-site selection would drive UK involvement in Mars lander missions. The organizers and participants (below) summarize the conclusions of the workshop and their overview of current and future priorities in the UK search for signs of life on Mars.

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The great unanswered scientific question "Is there life elsewhere in the universe?" can be addressed by exploring the only other planet in the solar system to have shown evidence of surface water during its past: Mars. The process of selecting a landing site for such an exploration mission, taking into account conditions for habitability now and in the past, will maximize its chances of success – and the chances of significant UK involvement, given our national strengths in the field.

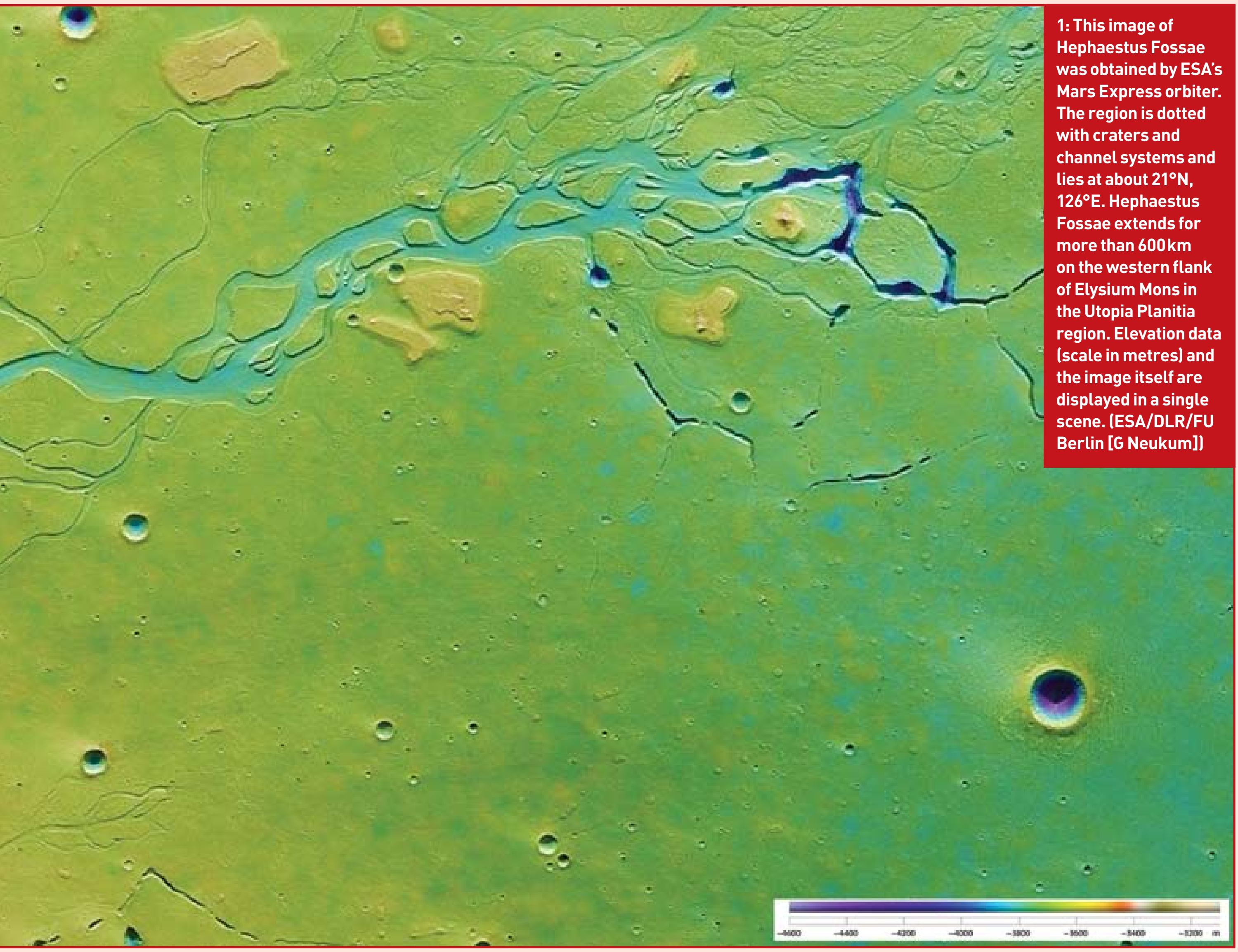
In 2004 and 2005 the Particle Physics and Astronomy Research Council (now the Science and Technology Facilities Council), undertook an extensive consultation exercise with the UK scientific and industrial communities over UK priorities for the European Space Agency's Aurora programme. The core priority agreed was to establish a strong UK position in an eventual robotic Mars Sample Return (MSR) mission. In 2008 a paper produced by STFC entitled "A UK roadmap to Mars Sample Return" outlined strategy to provide a framework for UK involvement in such a mission.

As part of this process, a workshop discussing landing sites and habitability on Mars was held at the Open University in the UK in June 2009, bringing together researchers in martian geology, exobiology, biogeochemistry, remote sensing, instrumentation and mission planning. This was organized to consolidate the UK planetary community view on identifying key landing terrains for future missions to Mars. The workshop focused on two questions:

- What makes a suitable landing site on Mars?
- How will such sites be identified for the sample-return missions anticipated in the future?

As the third largest contributor to Aurora, the UK needs to participate in the process that will eventually lead to decisions on landing sites for rover missions that will explore Mars's surface, identify favourable environments for life, search for evidence of past and present life and eventually return material to Earth.

The workshop addressed the scientific questions about prospective landing sites on Mars, outlined the different requirements – astrobiological, engineering, geographical, sampling



1: This image of Hephaestus Fossae was obtained by ESA's Mars Express orbiter. The region is dotted with craters and channel systems and lies at about 21°N, 126°E. Hephaestus Fossae extends for more than 600 km on the western flank of Elysium Mons in the Utopia Planitia region. Elevation data (scale in metres) and the image itself are displayed in a single scene. (ESA/DLR/FU Berlin [G Neukum])

methods – for the evaluation of different candidate terrains, summarized existing UK activity and expertise in these areas, and considered the future planning needs in order for the UK to assume a leading role in landing site selection.

Signs of life on Mars

The astrobiological potential of Mars lies in the evidence for liquid water and the assumption, based on our knowledge of terrestrial biology, that this is the fundamental requirement for life. Life requires a diversity of elements for its growth; at least carbon, nitrogen, phosphorus, oxygen, hydrogen and sulphur, although many other trace elements are required by particular organisms (such as, for example, tungsten needed by some anaerobic microorganisms). However, without a solvent in which to carry out biochemical reactions, it is assumed that life could not persist in any environment.

The identification of areas where life may have existed in the past requires orbiter imagery combined with spectral characterization, together with local analyses made by a mobile lander.

> **"Large volumes of water ice exist permanently in the martian northern and southern polar ice caps."**

For instance, orbiter imagery and landers from multiple missions have shown that much of the ancient highlands of Mars are composed of layered sediments, e.g. playa lake sediments at the Mars Exploration Rover (MER) Opportunity landing site (Grotzinger *et al.* 2005). But the majority of the sedimentary rocks there are aeolian rather than water-lain in origin, and so are expected to have a lower exobiological potential. There is considerable evidence for past water on Mars. Massive outflow channels in the northern hemisphere almost certainly arise from catastrophic flooding events, whereas dendritic drainage channels in the southern hemisphere may be the result of precipitation (Masursky 1973, Warner *et al.* 2009) or groundwater sapping (Laity and Malin 1985). Rover observations also suggest the presence of hydrated magnesium sulphate minerals (Peterson and Wang 2006). When studied from orbit by the Mars Global Surveyor, this landing site showed IR spectra of hematite iron oxide – indicative of water in the past (Christensen *et al.* 2000).

Large volumes of water ice exist permanently in the northern and southern polar ice caps. Subsurface ice is likely at lower latitudes (Boynton *et al.* 2002). Glacial features have been imaged on the surface landscapes of the planet and in the subsurface by radar. Liquid water is now unstable on the surface of the planet because of the low temperature and atmospheric pressure on the surface. However, in a recent study Balme and Gallagher (2009) showed that much of the equatorial regions of Mars had periglacial landscapes indicating surface ice with some meltwater within the past few million years.

The story of water on Mars over the past 250 million years, at least, is strongly affected by obliquity-driven climate change on the planet. Recently predicted periodicities in the obliquity of Mars (e.g. Laskar *et al.* 2004) mean that global stability fields for water are likely to have changed as a function of time and there is growing geomorphological evidence for obliquity-driven deposition of layered material on Mars (e.g. Head *et al.* 2003, Bridges *et al.* 2008). Theoretical studies of permafrost stability predict that water ice may be stable even in near-equatorial regions in periods of high obliquity (Mellon *et al.* 1997).

Hydrogen-rich near-surface soil (<1 m) detected from orbit correlates with the predicted stability of water ice, indicating a subsurface layer that may be on average ~60% ice by volume (Boynton *et al.* 2002). The past and present distribution of permafrost can also be determined from morphological features including rampart craters, debris flows, softened terrain, chaotic terrain, patterned ground, rootless cones and pingos (Squyres *et al.* 1992). At a given depth, as a result of the overburden pressure and/or geothermal gradient, subsurface ice can melt and the water occupy rock pore spaces as an aquifer (Clifford 1993).

The presence of gullies and seeps at >30°S on south-facing slopes within impact craters also suggests liquid water at the surface in geologically recent times. However, the precise origin of these gullies remains uncertain at present. Thus the search for past and present life is not limited to the ancient (Noachian) terrains on Mars.

Any search for and study of putative extant life must access the subsurface; developing drilling technology might become a high priority for UK researchers. The search for extinct life would also benefit from access to the subsurface, because of the surface layer of dust or unconsolidated sand and rocks. The depth of penetration to the subsurface will depend upon the sample site, but the general objective is to get to depths where liquid water and/or remains of past life might plausibly be found, protected from surface erosion and oxidation. This may be as shallow as two or three metres (for example, to access surface dust-covered ancient hydrothermal deposits) or as deep as kilometres (for example, to reach subsurface aquifers).

Recently, seasonal concentrations as high as tens of ppb of methane have been detected by Earth-based observations of some localized regions on Mars (Mumma *et al.* 2009) after methane had first been detected by ESA's Mars Express mission in 2004 (Formisano *et al.* 2004). The origin of the methane is unclear and its seasonality is unexpected – the residence time in the martian atmosphere was expected to be hundreds of years. This suggests mechanisms for actively releasing, capturing or breaking down methane – possibly biological – but further study of the distribution and the environment of release on Mars are necessary in order to assess scenarios for its formation.

Any environment where there is or was liquid water is a high priority for the search for life, but particularly optimal sites are ones with geochemical diversity that increase the chances of redox couples and nutrients for life. Given these conditions, three breakout groups at the workshop each independently considered the astrobiological potential of different terrains on Mars, identifying terrain types likely to be of high importance on Mars. The purpose of the meeting was not to identify specific landing sites for missions; these decisions are better left to specific landing site selection processes for each mission. Instead, the community sought to identify types of general terrains of high astrobiological potential. These sites are briefly listed below with some comments on relevance for the search for extinct or extant life.

- **Subsurface sites** in locations where there was or is geochemical turnover and potential for heat sources, e.g. impact craters, volcanic regions. Subsurface access is optimal for most landing sites on Mars. Given that atmospheric pressures were probably higher in Mars's past, preservation of extant microbial cellular structure may be most likely at pressures approaching 1 bar, equivalent to ~3 m burial depth on the planet. However, traces of microbial structures that had evolved to exist in a low-pressure martian environment could be found at shallower depths.
- **Permafrost regions/water ice.** Some permafrost and glacial ice in equatorial regions may have melted during periods of high obliquity within the last 10 Myr, providing liquid water habitats.
- **Bedded sediments.** These have a variety of origins on Mars including aeolian, deposition of dust from the atmosphere, fluvial and deposition within standing water. Sediments of aqueous origin represent high-priority targets for the search for past life. Included within this category are deposits of salts, including the substantial sulphate deposits.

> **"The search for extinct life will depend upon the survival of molecules in the rock record."**

- **Hydrothermal systems.** Evidence for silica-rich hydrothermal deposits on Mars at the MER Spirit landing site suggests that warm, water-rich geothermal habitats may have existed for early life on Mars. These sites would be high-priority targets in the search for extinct life.
- **Areas of high atmospheric methane concentrations.** The detection of methane on Mars has ignited a debate about whether the gas is of geological or biological origin. Subsurface access to gather samples will be challenging but necessary, and rovers that could sample methane gas and study its isotopic composition are a high priority for enabling the search for extant life. The workshop recognized the need for much more information on the spatial extent and mechanisms of methane production.
- **Caves/fractures.** Caves and other natural cavities/fractures provide protected subsurface environments that could plausibly be environments of interest in the search for extinct or extant life. These sites would cause formidable access problems, but might be promising for life.
- **Excavated material.** Subsurface material is naturally excavated by impact events, requiring less drilling, which could be examined for evidence of past and present life. Very recent impact events such as those identified by the Mars Global Surveyor would provide suitable examples if situated favourably for examination by a rover.
- **Ancient weathered rocks.** Phyllosilicates identified in the ancient highlands (and also in martian meteorites) formed in the presence of water and so make these high-priority regions. Regions where there are large concentrations of the aqueous weathering products of basaltic materials (e.g. phyllosilicate and carbonate) are also high priorities for the search for extinct life on Mars.

Within each of these priority landing areas a key focus will be the search for molecules indicative of life. The priorities for particular biomarkers have been discussed elsewhere (Parnell *et al.* 2007). For extant life, priority biomarkers (accepting the limitations of terrestrial life as a benchmark) are those common to all life such as lipids, nucleic acids and molecules widely found in life such as adenosine triphosphate. Stable isotope fractionation of the components of these molecules and gaseous waste products of life would also be a high priority.

The search for extinct life will depend upon the survival of molecules produced by once-living organisms in the rock record. Most promising among these are the lipids and molecules associated with cell membranes such as hopanoids. Signatures of life common both to extinct and extant life include the search for chirality in amino acids or sugars.

Engineering considerations

The choice of an astrobiologically interesting landing site must be placed in the context of what is practically achievable with current landing technology. In the selection process, engineering considerations are applied as a filter to the entire range of desired sites, to discern which areas are "reachable and feasible" within current mission capabilities. The main constraints on the positioning of landing sites on Mars are latitude, elevation, surface topography, slopes at different scales and the nature of the surface. Both rocky and dusty areas prohibit landing and rover operation. Environmental modelling

2: The High-Resolution Stereo Camera (HRSC) on board ESA's Mars Express has returned images of Echus Chasma, one of the largest water source regions on the Red Planet. Echus Chasma is the source region of Kasei Valles, which extends 3000 km to the north. The image is centred at about 1°N, 278°E and has a ground resolution of ~17 m/pixel. The dark material shows a network of light-coloured, incised valleys that look similar to drainage networks known on Earth. It is still debated whether the valleys originate from precipitation, groundwater springs or liquid or magma flows on the surface. (ESA/DLR/FU Berlin [G Neukum])

(e.g. wind speeds and temperatures) also play a critical part of this planning.

Delivery of landers from orbit has the advantage of reducing landing ellipse size and means that dust storms can be avoided. Direct hyperbolic delivery of landers (e.g. as used with airbags for the MER in 2003 and 2004) can also be successful, although landing ellipse sizes are unlikely to be less than ~150 km long.

The engineering constraints primarily fall under the umbrella of the Entry, Descent and Landing System technology (EDLS), which covers the portion of the mission from release from orbit (or ballistic entry) all the way to final deployment of the landed element. In addition to this there are "implementation" constraints, which cover operations of the landed element and its function/survival. Examples of EDLS constraints on landing site locations for an airbag type landing are:

- Low altitude (i.e. providing enough atmospheric drag for deployment of EDLS).
- Low probability of surface obstacles and small rock-size distribution for airbag landing.
- Regional low horizontal winds and turbulence for airbag or free-fall landing.
- Areas of minimized slope variations.
- Adequate radar altimeter reflectivity for descent and landing control.

In addition, operational constraints such as power available for solar panels place hard limits on accessible areas. For instance, using solar power limits feasible landing sites for long-term missions to equatorial and mid-northern latitudes. For a rover mission, the area of investigation must also be physically traversable (i.e. suitable for rover locomotion). Novel areas such as fissures and caves may force a change in the type of power source, perhaps to radioisotope thermoelectric generators, for example.

The constraints outlined above stem from the current EDLS/operations technologies and approach; however, as our understanding of landing on Mars develops and new methods emerge, some of these constraints will be removed, allowing access to a wider variety of locations. The potential for some sample caching from previous Mars surface missions, and hence the idea that MSR should be directed at a site that has already been explored by a rover, mean sample-return planning may in practice necessarily be intertwined with planning for the prior rover missions.

A critical part of landing site selection now includes surveying and the preparation of accurate digital elevation models to assess feasibility and risks. Orbital imaging is now capable of such high resolution that it can be used to survey candidate landing sites in detail to identify potential hazards and assess suitability and risks. Such surveying is of critical importance in assessing engineering constraints and providing pre-investigation and scientific assessment of the landing site. Consideration needs to be given to the continued supply of imaging data compatible with landing site selection for future missions as potentially complex as an MSR mission. For instance, the current HiRise imager aboard Mars Reconnaissance Orbiter is particularly valuable in this respect; it has stereo imagery available at 25 cm/pixel and 10×6 km surface coverage. The NASA Mars Science Laboratory landing site selection process relies heavily on these imagery data. But new imagery from MRO will be limited because of the lifespan of the orbiter (Grant *et al*. 2009)

A primary factor in determining risks is the size of the predicted landing ellipse on the surface. By using more accurate and controllable landing techniques (e.g. the Mars Phoenix controlled descent system), the landing ellipse can be minimized. This allows targeting of kilometre-scale areas of interest, providing rover access to areas of variable terrain. The traditional airbag landing system severely limits the landing location; landscapes with large-scale rock distributions are unsuitable, and the lack of control during descent leads to large landing ellipses. Future NASA Mars landings based on the "sky-crane" design, with a 10–15 km long landing ellipse (Grant *et al*. 2009) show potential. Controlled and accurate EDLS systems will be a major requirement for future missions to areas of astrobiological interest.

Access to landing sites and collection of samples

During and after the 1970s Viking missions it became obvious that the surface and near-subsurface of Mars are not homogeneous – a sample's location directly influences its content (NRC 1977). This inhomogeneity exists on scales of a few metres or less. Thus, landing at one site may produce one type of sample, but just metres away – or even closer in the subsurface – there may be other materials with a different story to tell. Engineering requirements for a safe landing may favour a landing site some distance from the area of primary scientific interest. To gain as full a picture as possible from a limited number of missions – potentially a single mission – several geographically separated sites may have to be sampled in one mission to collect a range of geological samples (see MEPAG 2008). Even at a landing site, the lander will not touch down next to exposed vertical surfaces, but there may be opportunities for sample collection with limited drilling.

For all these reasons the lander will need mobility to get to interesting samples. Even with precursor information, the site may still be relatively unknown so that a lander will need some search capability, to identify the most

Table 1: Characteristics of sample collection methods

surface mobility	
range: km	essential
sampling reach: cm – 10s of cm	essential
lifetime: months	essential
sample storage onboard	essential
imaging: camera (global context) and spectral analysis	essential
imaging: microscope (local context)	essential
in situ materials characterization (Raman/X-ray/Mössbauer etc)	essential
steep slope sampling	not needed in early missions
subsurface access	
imaging radar	desirable
drill (metre depth)	essential
capable of drilling more than one shaft	essential
corer for bottom of drill shaft	essential
sample extraction from wall of shaft	desirable

interesting collection points. The subsurface may contain materials with a different content to the heavily weathered surface – inaccessible without a drilling capability. An additional driver for mobility and drilling is the likelihood that any putative life on Mars (extant, remnant or extinct) will probably be at low density. If there is evidence for life on Mars it will have to be found by active searching; it is unlikely to just happen to be in any random sample of collected material. These points were made in a recent review of NASA activities concerning Mars exploration (NRC 2007).

The joint requirements for a search capability after landing, *and* the need to sample a variety of materials other than the ones on which the spacecraft lands, show a clear need for mobility and subsurface access.

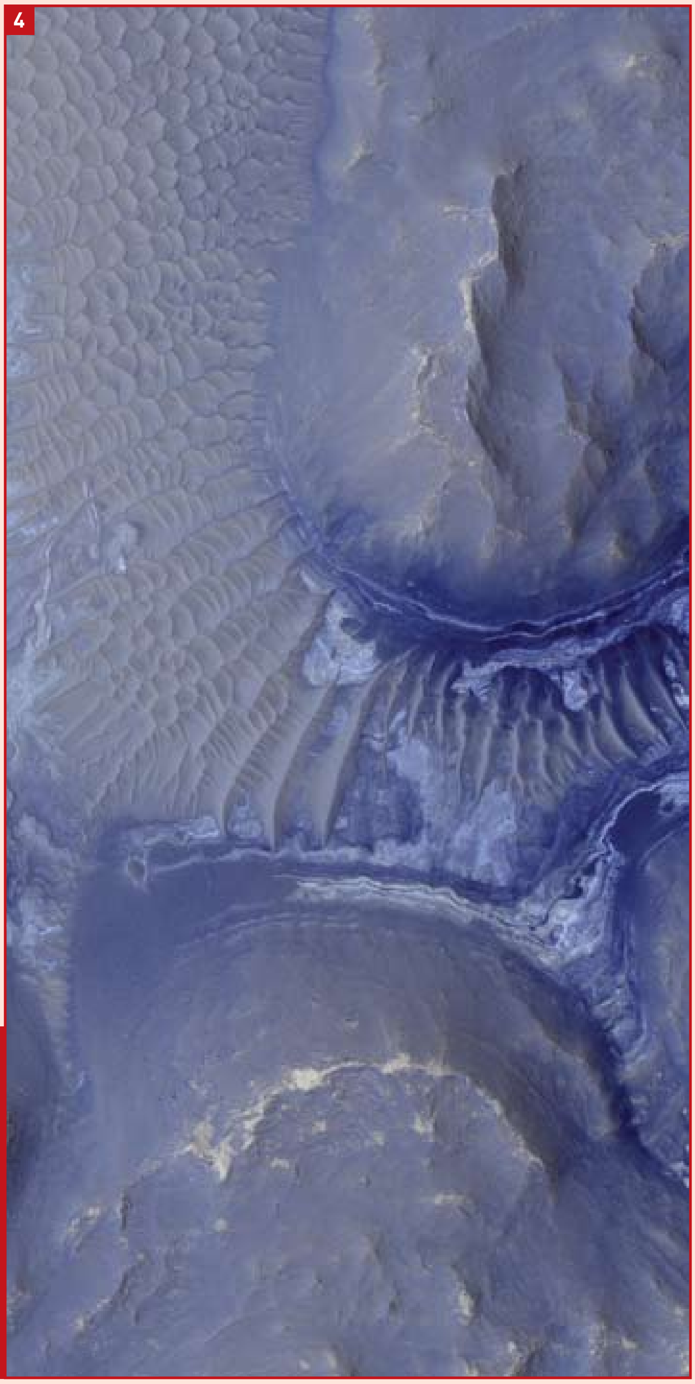
For these reasons, recent Mars missions have favoured rovers rather than fixed-site landers, permitting searches across tens of kilometres of the martian surface. However, the pace is slow; traversing and observing kilometre-scale distances is a lengthy process for rovers. This is a constraint on a sample-return mission – the rover has to be able to search, collect and return to the landing point. Rovers are not infinitely flexible; they cannot climb all gradients, nor operate on all surfaces (i.e. they need traction). To date their subsurface search capability has been limited, though future Mars rovers will have subsurface mapping and sampling capabilities. Issues related to mobility will limit the potential landing sites. Martian polar sites will almost certainly be considered inaccessible because they increase the mass that must be delivered to the planet's surface and present significant mobility hazards.

The mobility and subsurface criteria for an "ideal" roving Mars mission are summarized in table 1. The range of any rover will be limited by engineering and power capabilities. While an open-ended search at large distances may hold great potential for sample selection, maximizing the chance of finding suitable samples, it increases the risk of failing to make it back to the mission vehicle for the "return" phase. Therefore, any rover will have some maximum limit for ranging. It has been proposed that this should coincide with the size of the landing ellipse (e.g. see iMars 2008). This permits mission planning to focus on an area of interest (which given current limits on landing is still a large area, several kilometres across). However, this may present a conflict between the engineering constraints for a safe landing and the science need for access to a range of samples.

Sample characterization during collection will be important, of both the large-scale sample area and the finer texture of individual samples. Thus mobility is not sufficient by itself. It must be combined with instrumentation to define the particular environments that are visited to permit selection of the "right" samples and characterize their context. This will take some combination of instruments. The large-scale imaging can be combined with rover navigation and a higher resolution camera (e.g. as in the PanCam for ExoMars, Griffiths *et al*. 2006). One recent consideration is that, if the newly formed gullies indicating outflows of subsurface material are to be sampled, rovers will need to be able to reach steep slopes. This is beyond most current rover designs. However, it has been proposed that tethered rovers can be used to sample such deposits (Nesnas *et al*. 2008). Tethered rovers could be used on slopes up to 40°; they are lowered, take samples, and are then drawn back up the slope using the tether. This design would, however, add mass to a rover; also, the technique has not yet been demonstrated off Earth. Although this may not feature on a Mars Sample Return mission in the foreseeable future, we should be open to the possibilities of new technologies for traversing and accessing the surface and subsurface.

There will also be a need to store samples onboard a wide-ranging rover, which means that

3: This image shows the wall of a crater in the Northern Lowlands that has several gullies incising it, located at 55.8°N. How gullies formed remains elusive. The main problem is that liquid water is not stable on the surface of Mars due to the present-day pressure and temperatures. Gullies may be the result of a fluid (carbon dioxide or water), or they may be the result of dry debris flows. The gullies in this image source from a similar distance from the crater rim and terminate down the slope in relatively bright deposits. They also have debris-free alcoves and exhibit other features typically formed by water flow, including a sinuous channel shape, channels that merge and split forming a braided pattern, and channels that extend out onto the debris fan deposits. One theory is that the similar elevation of the sources below the crater rim may indicate that groundwater flowed out of the crater wall along a subsurface rock or soil layer. Salts and minerals in the groundwater may have allowed the water to continue flowing on the surface longer as a liquid. Continued flow would eventually erode the surface, forming a gully. (NASA/JPL/Univ. of Arizona)



4: Layers in the lower portion of two neighbouring buttes within the Noctis Labyrinthus formation on Mars are visible in this image from the HiRISE camera on NASA's Mars Reconnaissance Orbiter. The view covers an area about 1 km wide at 11.2°S, 261.8°E. Dune fields blanket the ground in the upper left and a portion of the ground between the buttes. Exposures of brighter and darker materials are also visible in the portion of that area not covered by the dunes. Observations of this region of Noctis Labyrinthus by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the MRO have shown indications of iron-bearing sulphates and phyllosilicate (clay) minerals. The exposed layers revealed in HiRISE observations of the area might be the sources of the mineral signatures seen by CRISM. (NASA/JPL-Caltech/Univ. of Arizona)

cross-contamination will need to be avoided. For subsurface samples, temperature control during storage may have to be addressed. The drilling method should also minimize processing of samples, by heating or fracturing, for example, during the drilling process. A review of drilling methods is given in Zacny *et al.* (2008) and an example of robotic drilling in Arctic conditions is provided by Glass *et al.* (2008).

The need for subsurface access imposes significant constraints on a rover. To select where to drill based solely on surface imagery is of limited value. Although blind experiments with robotic drilling have shown that drilling and analysis of the cores can produce a fairly accurate interpretation of the subsurface in a region (e.g. Stoker *et al.* 2008), this is not the issue here. The question is: given only a limited number of drilling opportunities, where do you choose to drill? This implies a need for a subsurface imaging capability or the capability to characterize the mineralogy of outcrops. On the enhanced ExoMars mission, originally destined for launch in 2013, subsurface imaging would have been provided by WISDOM, a ground-penetrating UHF radar capable of penetrating a few metres. The depth to which a drill needs to penetrate must also be fully defined as it in turn imposes constraints on drilling technology and the mass budget for the rover. One relatively under-discussed topic concerns whether drill samples should be solely cores or if lateral sampling should be done from the drill shaft as well. This technology is available for sampling wells in the oil industry.

"Sample caching from missions prior to sample return would help reduce some risks."

All apparatus can fail. The more complex an instrument, and the more demands placed upon it, the greater the risk of failure. If a Mars Sample Return mission includes both a rover (for mobility) and a drilling capability, these represent single-point failures. If the rover breaks down or becomes stuck during its sampling mission, no samples will be returned to the lander.

Similarly, if the drilling apparatus fails, or the drill bits become stuck during deployment, no samples could be collected. Despite the need for mobility and subsurface access, the need remains for sample collection at the site of the return vehicle (iMars 2008). There should be a simple collection method (e.g. a scoop such as that on the Mars Phoenix lander) used early in the mission to obtain a minimum sample including some shallow subsurface material and deliver it to the return vessel. Sample caching from missions prior to sample return, in addition to sampling during the actual mission itself, would also help reduce some risks such as malfunctioning equipment. This raises the question of whether, for maximum scientific return, a sample-return mission should be limited to a site that has already been studied by a rover.

As part of this work, a survey of the 100 most recent papers in Web of Science was carried out searching for the phrase "Mars Sample Return" (August 2009). None of the 100 papers was focused on the needs for collection of the samples themselves, while many papers concentrated on individual issues such as the return of the sample, planetary protection, sample analysis, rovers or drilling, or they gave general overviews. Nevertheless, selecting the optimal samples is at the heart of any sample-return mission. This in turn imposes constraints on the mission in terms of mobility and subsurface capability. Given that these requirements come with substantial mass burdens, which will affect the overall design and planning of the mission, a full understanding of sampling requirements should be considered paramount.

Landing site access will also depend upon planetary protection policy. This was not considered in detail by the workshop, but it is recognized that "special regions" on Mars (regions in which extant life may support Earth microbes inadvertently introduced to Mars, or that may have a high probability of supporting indigenous martian life) (Rummel 2009) will be regions where rigorous sterilization of spacecraft will be required. These factors, when more fully refined, will constrain landing-site selection and/or required sterilization protocols.

Existing activity and UK expertise

The UK has a strong expertise in astrobiology with many universities developing a strong presence in the field. For instance, research groups at the Open University focused on microbiology have developed an understanding of the limits of life in extreme environments and the response of organisms to simulated extraterrestrial conditions, which is necessary to assess habitability on other planetary surfaces. Sites on Earth such as dry Antarctic valleys that are analogues for some of the terrains on Mars are also being actively investigated. The UK has developed state-of-the-art technology for the detection of life on other planetary surfaces, and considerable expertise in the detection and study of biomarkers in extreme environments has been developed at the universities of Leicester and Bradford and Imperial College London. The UK has expertise in mass spectroscopy, for example at the Open University, Manchester University and the Natural History Museum, that has been used extensively in meteorite studies and could be applied to the study of the isotopic signatures of life on other planets. The UK has also been prominent in the detection of atmospheric components on exoplanets, with leading researchers at University College London heavily involved in the first detection of exoplanetary water vapour, methane and carbon dioxide.

The community recognized the importance of remote sensing for a thorough characterization of potential landing sites prior to the mission. The UK has an active planetary remote-sensing community. For instance, recent work by UK groups – MSSL/UCL, Open University, University of Leicester, British Geological Survey, Imperial College – has included using remote sensing and IR spectral characterization to study layered sediments, dust devils on the martian surface, periglacial terrains in the equatorial regions of Mars and catastrophic flood deposits. This expertise forms the basis for understanding likely landing terrains. It is essential, for instance, in order to understand the origin of any target sediments.

In 2005 researchers from the Open University and the Mullard Space Science Laboratory (MSSL) used the Mars Express High Resolution Stereo Camera and Mars Orbiter Camera imagery to suggest the presence of a frozen ocean in the Elysium region of Mars. This has stimulated ongoing discussions about the history of water and volatiles on Mars. If large standing bodies of water existed in recent geological epochs on Mars, this has profound implications for understanding the habitability of Mars throughout its history – and for selecting potential landing sites for Aurora landers.

"The current ExoMars rover prototype and robotic arm are being developed in the UK."

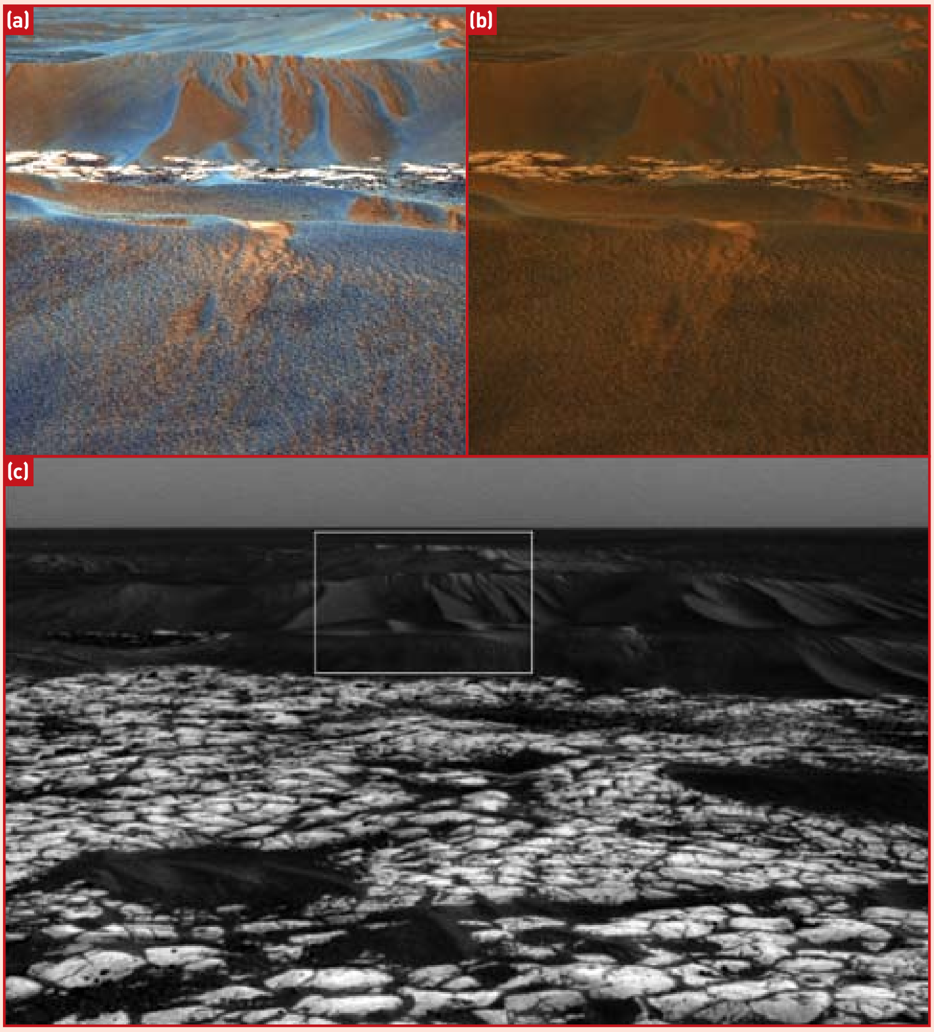
UK scientists also have a major involvement in the HRSC experiment that started returning images in 2003. Scientists from the MSSL and the NASA Regional Imaging Facility at University College London have produced some of the most accurate digital elevation models of Mars. This is an essential technique for landing site characterization and verification, both for habitability prioritization and safety considerations.

Cosmochemistry from martian meteorites is a UK strength. Following the first description in 1975 of secondary veins in the Nakhla meteorite, UK researchers have taken a major role in studying the effects of hydrothermal alteration in the Shergotty-Nakhla-Chassigny (SNC) meteorites. In addition to helping in the understanding of martian crustal and hydrothermal processes, the UK SNC meteorite and cosmochemistry expertise provides a foundation for Mars Sample Return missions. For instance, understanding of crustal hydrothermal processes from the study of nakhlite meteorites will be critical in understanding clay-rich terrains where MSR sampling might take place.

The SNC meteorite group has been identified as martian impact ejecta since their trapped gas compositions were compared to those of the martian atmosphere. Studying secondary alteration phases has been a major stimulus to research into past environmental conditions on Mars. The Open University has used carbon isotopes of low-temperature minerals in the meteorites to describe the carbon cycle on Mars. Open University and Natural History Museum researchers also used oxygen stable isotopes to constrain the low temperature of crystallization (<150 °C) of carbonate grains in the ALH84001 SNC meteorite. Subsequently, in 1996, a group of NASA researchers suggested that those carbonate assemblages in ALH84001 were of biogenic origin. By use of Ar–Ar isotopes, UK researchers at Manchester University played a major part in deciphering the age and history of hydrothermal alteration in the martian crust recorded by this meteorite. Electron microscopy and transmission electron microscopy in UK laboratories of alteration phases within the nakhlites at the universities of Leicester, Glasgow and the Natural History Museum and the Open University have led to a widely used model of low-temperature alteration involving brine evaporation. Understanding the formation of carbonate–clay assemblages in the SNC meteorites is providing models that will help explain the origin of these minerals on the Mars surface.

Stimulated by the 2003 Beagle 2 mission, the UK has built up expertise in instrumentation for robotic missions from ExoMars to Mars Sample Return. Within the UK, X-ray diffraction XRD (Leicester), Raman (Leicester, Bradford) and stereo camera PanCam (MSSL) and UV-VIS spectrometer (Open University) instruments are being developed for the Mars robotic programme with European collaborators, and these will allow mineralogical characterization, detection of organic compounds and will help identify fossil or extant life. Other techniques for life detection (e.g. measuring chirality) that are being developed for future missions are the Urey instrument, which is a joint US–UK (Imperial College) experiment, and the UK-led

5: These images were acquired by NASA's Mars Exploration Rover Opportunity using its panoramic camera (a and b) and its navigation camera (c). The view looks towards the east, covering a large wind-blown ripple called "Scylla", other nearby ripples, and patches of brighter rock strewn with dark cobbles.
(a) Panoramic camera bands L4 (601 nm), L5 (535 nm), and L6 (482 nm) correspond to red, green and blue bands in the false-colour image. The blue-tinted colours associated with the scours and ripple crests are probably due to the presence of basaltic sands mixed with hematite-rich spherules. Colour patterns on the larger ripple flanks are caused by different amounts of reddish dust. The larger ripple flanks have an intricate mixture of erosional scours and secondary ripples extending downward from the main ripple crests, suggesting that these ripples have most recently encountered a period of wind erosion and transport of their outer layers.
(b) For comparison, the same panoramic camera image is shown, but rendered as an approximately true-colour composite.
(NASA/JPL-Caltech/Cornell)



Life Marker Chip at the University of Leicester. In order to test the habitability of landing sites it is necessary that the instrumentation set chosen for a mission is fit for purpose and can determine many of the mineralogical and chemical signatures of life. This requires communication between instrument teams and the wider Mars research community. An example is the ability to characterize clays by X-ray diffraction, as these are markers for the past presence of liquid water near the surface. For sample-return missions in particular, it is essential that appropriate samples are chosen. This requires a mineralogical, imaging and geochemical instrument set together with the capability to drill (iMars 2008). Drilling emerged as a key technology in the discussions at the workshop, but at present expertise in the UK for non-terrestrial drilling is limited. The requirement for vertical drilling capability makes this an area of high potential interest. The possibility of horizontal drilling into rock outcrops was also discussed as a desirable goal.

The UK has built up a significant expertise in planetary robotics. In particular, the current ExoMars rover prototype and robotic arm are being developed in the UK by an academic/industrial consortium. A research group at the University of Aberystwyth is developing robotic technology for this rover prototype and for future rover missions, including autonomous navigation procedures. The latter will become an important part of future missions, allowing greater distances to be covered in the time available on the planet's surface, because it will cut the time between a target being identified and the rover actually acquiring the sample. Advanced robotics research and novel power sources are two of the elements of the robotic space exploration programme that will feature in the new ESA facility at STFC's Harwell Science and Innovation Campus. Radiogenic power sources (e.g. as used in the Spirit and Opportunity MER) may thus offer a high-priority area for development. These will facilitate long-duration missions and enhance mobility and rover speed, thus boosting the sampling of diverse geological terrains on Mars.

Future planning

It is important to increase the momentum that has already been built up by the June 2009 workshop. This could mean further workshops pursuing a range of themes related to the areas of UK expertise stated in the summary, either annually or biennially. A possible alternative is the setting up of a "UK Mars Group" to help stimulate research on habitability, landing sites and the evolution of Mars and provide an identified focus for this high-priority area of science. It is envisaged that this would be a multidisciplinary group combining remote sensing, mission planning, instrumentation and mineralogical expertise that can focus on issues related to the Aurora programme of exploration. Formats for meetings to engage the wider community could include annual or biennial RAS meetings. Formal updates of this document could represent a UK community view of what it can bring to such discussions and be regarded as an expression of its interest in the same.

Design and construction of instruments and power sources to analyse landing sites and identify traces of life needs to be fully integrated with the science activities of the UK and wider Mars research community. Future workshops, following this model, that brought together people from a wide range of disciplines, could focus on several different topics, for instance bringing together researchers and engineers from both academia and industry.

Effective communication between engineers and the science community in the early stages of mission planning will enhance the chances

6: This approximate true-colour image taken by the Mars Exploration Rover Spirit shows the rock outcrop dubbed "Clovis". The rock was found to be softer than other rocks studied at Gusev Crater after the rover easily ground a hole into it with its rock abrasion tool. An analysis of the hole found higher concentrations of sulphur, bromine and chlorine compared to basaltic, or volcanic, rocks at Gusev. This might indicate that Clovis was chemically altered, and that fluids once flowed through the rock depositing these elements. (NASA/JPL/Cornell)

7: This approximate true-colour rendering from NASA's Spirit shows a set of darker rocks dubbed "Toltecs". These rocks are believed to be basaltic, or volcanic, in composition, because their spectral properties match those of other basaltic rocks studied in Gusev Crater. Scientists hope to use these presumably unaltered rocks as a geologic standard for comparison to altered rocks in the area, such as "Clovis". (NASA/JPL/Cornell)

of achieving the goal of finding evidence for life on Mars. This is already present to a significant extent and was highlighted by STFC's successful CREST (Collaborative Research and Exploration Space Technology) programme in 2006–7. This programme was initiated to develop UK technology priorities by enabling positioning of UK academia and industry for participation in future ESA missions and then to spin technology into other applications. Further CREST programmes are planned from 2010 onwards.

Planning for the Mars Sample Return mission requires selection of an appropriate landing site or sites where life is or may have been present. With the potential for sample caching from earlier landers (e.g. ExoMars), MSR planning needs to be fully integrated with the other missions. The limited lifespan of orbiters (e.g. Mars Reconnaissance Orbiter) potentially means that there is a limited amount of high-resolution imagery to be obtained for new sites after the next few years. Thus delay in considering landing sites might hinder the success of missions.

The search for organics and life on Mars remains one of the most compelling reasons for the exploration of Mars. Even if there are eventually found to be large areas without evidence of past or present life, it is equally important to understand the conditions that may have precluded its development. The UK community recognizes a number of terrain-types for priority landing targets on Mars, including ancient permafrost and sedimentary layers and regions of high methane abundance. Many of these sites have potential to harbour both extant and extinct life. The view held by most members of the community is that access to subsurface sites is required. UK strengths in the study of Mars and its habitability include remote sensing, astrobiology, landing capability, surface operations, instrumentation and analytical capabilities. All these fields have been successfully consolidated into a community. The community recognizes its desire to engage this expertise with Mars landing-site selection and the study of habitability in ESA and other space agencies. For this community to successfully develop and play an important and influential role in this process, it needs strong UK support.●

"The search for organics and life is one of the most compelling reasons for the exploration of Mars."

This article was prepared from the position document resulting from a UK Workshop at the Open University (4 and 5 June 2009).

Further reading

Position document http://tinyurl.com/ygkhxs2

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