Beyond water on Mars

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Mars exploration has been guided by the search for water. The more complex quest by Mars Science Laboratory for habitable environments should illuminate the Martian environmental history, and possibly deliver insights into extraterrestrial life.

We live in the golden era of Mars exploration. Two rovers and three orbiters routinely analyse the current and past states of the planet's environment. These missions build systematically on earlier explorations and all have performed well past their nominal operational period, each generating impressive and sometimes astonishing results. With all the hardware in motion around Mars these days, the most remarkable achievement of Mars exploration is the high degree of both tactical and strategic coordination among the missions. It is the combination of results from a variety of missions and instruments that has propelled us ever closer to fathoming the broad range of environmental processes that have transformed the surface of Mars, beginning over four billion years ago.

The unexpected dividends of these extended, overlapping and increasingly coordinated missions are rich: we now know that the surface of Mars has been transformed by interactions with water throughout its history. For the earlier 2,000 to 3,000 million years of Mars's history, the evidence for the presence of water includes recognition of very ancient basaltic crust that must have been altered by aqueous processes[1] to produce diverse assemblages of hydrated phyllosilicate minerals[2,3]; the discovery of vast sequences of thick, well-bedded sedimentary rocks of largely unknown origin and composition that clearly contain hydrated sulphates, phyllosilicates and opaline silica in some places[4–7]; the recognition of many local topographic depressions such as craters and structural troughs that are filled with alluvial fans and deltas that contain hydrated phyllosilicates[8–10]; and the revelation that the rich and varied history of Mars is characterized by a rock cycle that involves the accretion of materials (sometimes of aqueous origin), their burial, alteration and transformation in groundwater, followed by exhumation and their return to the surface[11]. The more recent history of Mars also provides evidence for aqueous processes, but not as widespread as in early eras.

The conclusion of a dominant role for water in shaping the planet's surface is exciting for science, but also reassuring to the programme administrators who adopted and bankrolled the 'follow-the-water' strategy. With the forthcoming rover Mars Science Laboratory, due to launch in 2011, this strategy will be refined to the search for past and present habitable environments.

Habitability and preservation

Loosely defined, a habitable environment is one that has not only water, but also a source of carbon to make organism metabolism possible, and a source of energy to fuel that organism metabolism — in other words, the essential ingredients for life as we know it on the Earth. To match the task, Mars Science Laboratory (Fig. 1) will be the most capable robot ever sent to the surface of another planet. It will search for organic carbon in rocks, in soils and in the atmosphere, determine mineralogical diversity in rocks and soils, image landscapes and rock or soil textures in unprecedented resolution, determine rock and soil chemistry *in situ*, remotely sense the chemical composition of rocks and minerals, search for water in rocks and soils, measure modern-day environmental variables and continuously monitor background solar and cosmic radiation. It will investigate one of four sites that have made the shortlist — Eberswalde crater (24° S, 327° E), Holden crater (26° S, 325° E), Mawrth Vallis (24° N, 341° E) or Gale crater (5° S, 137° E) — all of which show clear evidence for ancient aqueous processes based on data sent back to the Earth by current orbiting missions (Fig. 2).

The search for habitable environments is a big step. Mars Science Laboratory is not a life-detection mission. It does have the capability to detect complex organic molecules in rocks and soils, but would not be able to identify extant vital processes that would betray present-day microbial metabolism or to image

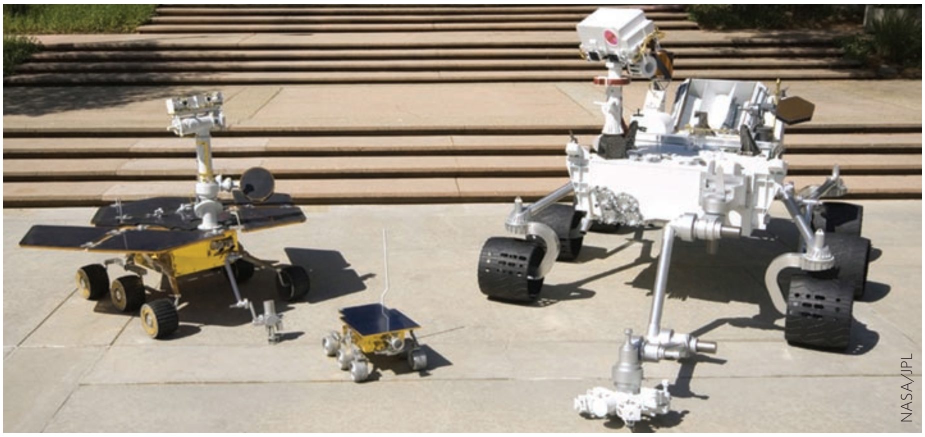

Figure 1 | Scale models of Mars Science Laboratory (right) next to Pathfinder (centre) and Mars Exploration Rover (left). The Mars Science Laboratory payload includes a gas chromatograph/mass spectrometer and gas analyser that will search for organic carbon in rocks, in soils and in the atmosphere; an X-ray diffractometer that will determine mineralogical diversity in rocks and soils; colour cameras that can image landscapes and rock or soil textures in unprecedented resolution; an alpha-particle X-ray spectrometer for *in-situ* determination of rock and soil chemistry; a laser-induced breakdown spectrometer for remote sensing of the chemical composition of rocks and minerals; an active neutron spectrometer designed to search for water in rocks and soils; a weather station to measure modern-day environmental variables; and a sensor designed for continuous monitoring of background solar and cosmic radiation.

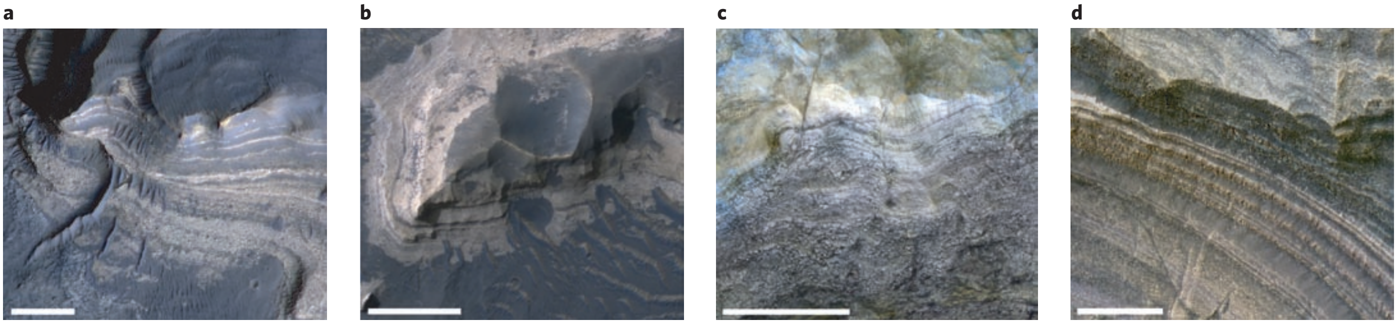

Figure 2 | Four potential landing sites for Mars Science Laboratory. Eberswalde crater (**a**), Holden crater (**b**), Mawrth Vallis (**c**) and Gale crater (**d**) have been shortlisted as the most promising sites for the search for habitable environments. The images were taken by the High Resolution Imaging Experiment (HiRISE) camera and show strata near the base of delta deposits for Eberswalde and Holden craters; strata near the top of a deposit several hundred metres thick that preserve a transition from iron-magnesium phyllosilicates (darker tone) to aluminium-rich phyllosilicates (lighter tone) for Marwth Vallis; and strata near the base of a 5-kilometre-thick succession containing interstratified sulphate and phyllosilicate deposits for Gale crater. All scale bars are 100 m. Images courtesy of NASA/JPL/U.Arizona/R. Milliken.

microorganisms or their fossil equivalents. Potential complex organic molecules might be of biological origin, but could also reflect the influx of carbonaceous meteorites. The main challenge in establishment of a biological signature is finding patterns, either chemical or textural, that are not easily explained by physical processes alone[12]. To help with this, Mars Science Laboratory will have the analytical capability to probe other less distinctive biosignatures, such as the isotopic composition of inorganic and organic carbon in rocks and soils, particular elemental and mineralogical concentrations and abundances, and the attributes of unusual rock textures. Finally, it will be able to evaluate the concentration and isotopic composition of atmospheric gases such as methane that could be of biological origin, as recently detected in the modern atmosphere[13,14].

Compared with the goal of finding evidence for past or present water, the quest for habitable environments is much more challenging, mainly because organic carbon — even if it were produced in abundance — would not necessarily be preserved well enough to allow its detection. Organic carbon is a reduced compound and is expected to have a short lifetime in the current Martian surface environment, which contains a variety of oxidants[15–17]. Furthermore, the sorts of environments where most biological signatures enter the rock record by becoming coated in stable minerals involve the circulation of oxidizing fluids that could decompose organic matter.

If we use the Earth's early geological record as a guide to the preservation of biosignatures in the ancient Martian rocks (assuming that microbes were once present on Mars), then we should prepare to be patient. Scientists working on the terrestrial record of early life learned long ago to focus on rocks whose preservation character maximizes the chances of success. Paradoxically, the very characteristics — water, oxidant supply and gradients in heat, chemicals, and light — that make so many environments habitable also cause them to be destructive to biosignatures. Nevertheless there are rare circumstances that lead to spectacular preservation; on the Earth, these often involve geochemical conditions that favour very early mineralization.

Mars Science Laboratory's search for organic compounds can therefore be optimized by pursuing an exploration strategy that focuses on finding windows of preservation. We should be guided but not limited by our terrestrial experience: Mars may have its own unique palaeoenvironmental conditions favourable to the preservation of organic compounds and other potential biosignatures.

Environmental records

An essential point that the Earth teaches us is that in the search for signs of early life a null result is not necessarily a disappointment. Whatever may be lost in terms of insight into possible palaeobiological markers may be gained in equally rich insight into the processes and history of early environmental evolution. Studies of the Earth's Precambrian sedimentary record, often aimed at identifying life, have revealed secular changes in the oxidation state, acid–base chemistry and precipitation sequence of minerals in the oceans and atmosphere[12,18,19]. An equally informative environmental history may also be uncovered on Mars. The history of surface environments on an Earth-like planet that lacked a biosphere would make a highly desirable comparison to the history of the Earth and could help us to understand the unique aspects of our own planet's history. Records of environmental history are embedded in the same kinds of rocks and minerals that may preserve the calling cards of biology. Therefore, a Mars Science Laboratory mission that focuses on understanding mechanisms of potential biosignature preservation will also ensure that we capture the record of early Martian environmental processes and history.

Each of the four shortlisted landing sites has its own particular strengths, and they have in common two very important attributes: definitive evidence for the former presence of water as shown by either mineralogical or morphological features (or both), and the presence of prominent stratigraphic sequences, hundreds to thousands of metres thick in some cases, suggestive of sedimentary rocks (Fig. 2). Historical accounts of planetary surface evolution are largely written in stone, and processes that operate at a planetary surface have the potential to create a record of sedimentary rocks. This is important because our experience on the Earth shows that sediments and sedimentary rocks can preserve high-resolution proxies of present and past climatic, tectonic and biological processes as well as providing the dominant archive of important events in a planet's evolution. Sedimentary rocks precipitated from water are particularly important because they embed signals of elemental and isotopic variability that relate to geochemical and biogeochemical processes, expressed at local to global scales. Although other rock types such as hydrothermal deposits in volcanic terrains also have potential to be both habitable and favourable for preservation of biosignatures, terrestrial experience shows that sedimentary rocks are the favoured medium for preservation of both biological signatures and high-resolution global environmental records.

Martian history

The French novelist Marcel Proust reminds us that the real voyage of discovery consists not just in seeking new landscapes, but in having new eyes. We are on the cusp of a fresh and exciting understanding of the early evolution of Martian surface environments, thanks to the eyes of the imaging spectrometers OMEGA and CRISM, and their counterpart HRSC and HiRISE cameras that orbit Mars at present. The emerging sense of chronology provided by their global-scale mineral and terrain mapping is a large step forward in decoding an important chapter in the history of Mars.

As current thinking has it, the long-term environmental evolution of the planet is delineated in the history of mineral assemblages: according to this idea, ancient Mars was characterized by alteration of ancient crust by neutral pH fluids to form phyllosilicate minerals, and then evolved into a planet where alteration by acidic fluids generated vast terrains of bedded sulphate minerals[20]. These younger bedded terrains could have formed by *in-situ* alteration of precursor igneous silicate minerals, accumulation of altered sediment particles transported from a separate source region, or *in-situ* accumulation of sedimentary evaporite minerals derived from acidic groundwater.

This view is both creative and potentially powerful. If this evolutionary model is correct, the age of the observed alteration minerals must be closely related in time to the parent rocks from which they are derived, and the detection of the minerals must stand up to independent testing. This is a strong motive for sending Mars Science Laboratory to a landing site that provides direct access to the phyllosilicate and sulphate mineral assemblages. All of the four potential landing sites host phyllosilicate minerals, and Gale crater may also preserve a transition from phyllosilicates to sulphates. Nevertheless, all of these sites offer the chance for Mars Science Laboratory to play a key part in the evaluation and development of our ideas on how Mars became the planet we see today.

The focus on habitability holds both the hope and the promise of Mars Science Laboratory. The hope is that we may find some signal of a biological process. The promise is that Mars Science Laboratory will deliver fresh insight into the comparative environmental evolution of the early stages of Mars and the Earth. That alone is a valuable prize. ❐

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