Lifeless Martian samples and their significance

Although a major objective in Mars exploration is the search for life, there are many scenarios that could lead to the recovery of lifeless samples. What could lifeless samples tell us about Mars and its habitability?

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Mars is today a cold desert world whose surface is thought to be largely uninhabitable[1]. However, the planet hosts abundant evidence for a more hydrologically active past[2,3] particularly in the Noachian (circa 4.1 to 3.7 billion years ago). These observations raise the question of how widespread habitable environments were and whether they hosted life.

Investigations of Gale Crater by the NASA Mars Science Laboratory (MSL) suggest that Martian lakes of moderate pH and salinity were redox-stratified and contained iron and sulfur in multiple oxidation states with the potential to yield energy for microbial metabolism ~3.7 billions of years ago[4,5]. Habitable conditions have also been suggested for the Phoenix landing site in Vastitas Borealis in the north polar region of Mars during past obliquity variations[6]. These findings support the hypothesis that Mars hosted conditions favourable for life and have revived interest in missions focused on the detection of preserved biosignatures[7]. The possibility of stable liquid water in surface and subsurface environments continues to motivate speculation about whether the planet hosts present-day habitable conditions[8,9].

Although approaches to finding evidence of life in Martian samples have been discussed extensively, little consideration has been given to the significance of recovering lifeless samples, that is, samples devoid of any discernible trace of past or present biological activity. Lifeless samples would provide significant insights into the habitability and biological trajectory of Mars. We discuss scenarios that might lead to lifeless samples, how those scenarios could be tested, and what research directions they motivate.

Lifeless Mars

The presence of habitable environments on Mars, at least with respect to known life on Earth, does not preclude the possibility that those environments were lifeless[10]. To begin with, Mars might never have hosted life in any environment (Fig. 1a). The conditions required for the origin of life on Earth are not precisely known. Some hypotheses suggest incompatibility between the conditions required for the origin of life and conditions on early Mars. For instance, deep-ocean alkaline hydrothermal vents formed by serpentinization at spreading ridges have been suggested as one context where life could have emerged[11]. However, although there is abundant evidence for serpentinization on Mars, the early cessation of plate tectonics and a lack of deep-water environments could have limited the abundance of appropriate vent sites and hence frustrated an origin of life. Alternatively, if the origin of life is a probabilistically rare event, it may never have occurred on Mars even if suitable environments were available.

In the absence of an independent origin of life, an alternative pathway for the establishment of life on Mars is via transfer from the Earth[12,13]. Experiments to simulate impact shock during launch from the Earth, multi-year studies of microbial survival in space, and experiments examining the viability of microorganisms after atmospheric entry all suggest that the different phases of 'lithopanspermia' from launch to arrival might be survivable. However, any one of these phases may have proved insuperable to Archean life. All experiments have been conducted using a modern microbiota and we do not know if early life would have had similar physiological tolerances. Lithopanspermia remains a theoretical possibility.

In view of these scenarios, several areas of research could be advanced. First, developments in our understanding of the origin of life and the search for environments on Mars conducive to this process might reveal whether life could have begun there independently[14]. Second, studies could be advanced to improve our understanding of whether any of the phase(s) of lithopanspermia could act as a sufficient dispersal filter to maintain Earth and Mars as biogeographical islands. Studies on the survival of diverse deep-branching microorganisms in interplanetary radiation conditions could reveal whether conditions were too extreme during the transfer phase in space, for example.

If the surface of Mars had become largely inclement by the time terrestrial life had achieved sufficient biomass to have a reasonable chance to inoculate Mars, then both planets may have remained biologically isolated. Comparisons between emerging knowledge about surface conditions on the early Earth and Mars would allow us to assess whether inappropriate conditions on Mars itself disallowed successful inoculation of early life evolved under Earth conditions.

Sparse biosphere

Even if Mars hosted life, samples collected now might be lifeless. In the absence of sustained plate tectonics, Mars became geologically impoverished compared to the Earth. On account of its small size and the loss of its magnetic field, it lost much of its atmosphere in the Noachian[15], truncating the surface hydrological cycle and rendering much of the surface uninhabitable, as it is today. These conditions could have stymied a biosphere by limiting water flow, restricting geochemical turnover and diminishing the availability of geochemical disequilibria as a source of free energy.

On the Earth today, photosynthesis produces a substantial quantity of organic carbon, which accounts for most of the biomass in surface environments. This organic carbon is continuously exported into soils, groundwater, lakes, rivers and oceans, where it may be reincorporated into biomass (with or without first remineralizing into CO_2 or CH_4) and/or used as an electron donor (typically for the reduction of oxidants also derived largely from photosynthesis). On Mars, extreme surface conditions, including ionizing and ultraviolet radiation, and a paucity of interconnected sustained bodies of surface water from the beginning of the Hesperian onwards, would likely have precluded such large-scale recycling and rendered any biosphere highly impoverished compared to the Earth[16].

These limitations to biomass distribution on Mars could lead to lifeless samples in four ways: (1) A generally globally habitable Martian environment was uninhabitable at the particular place and time represented by a sample (Fig. 1b); (2) Habitable regions or specific habitable locations were never inoculated with appropriate organisms

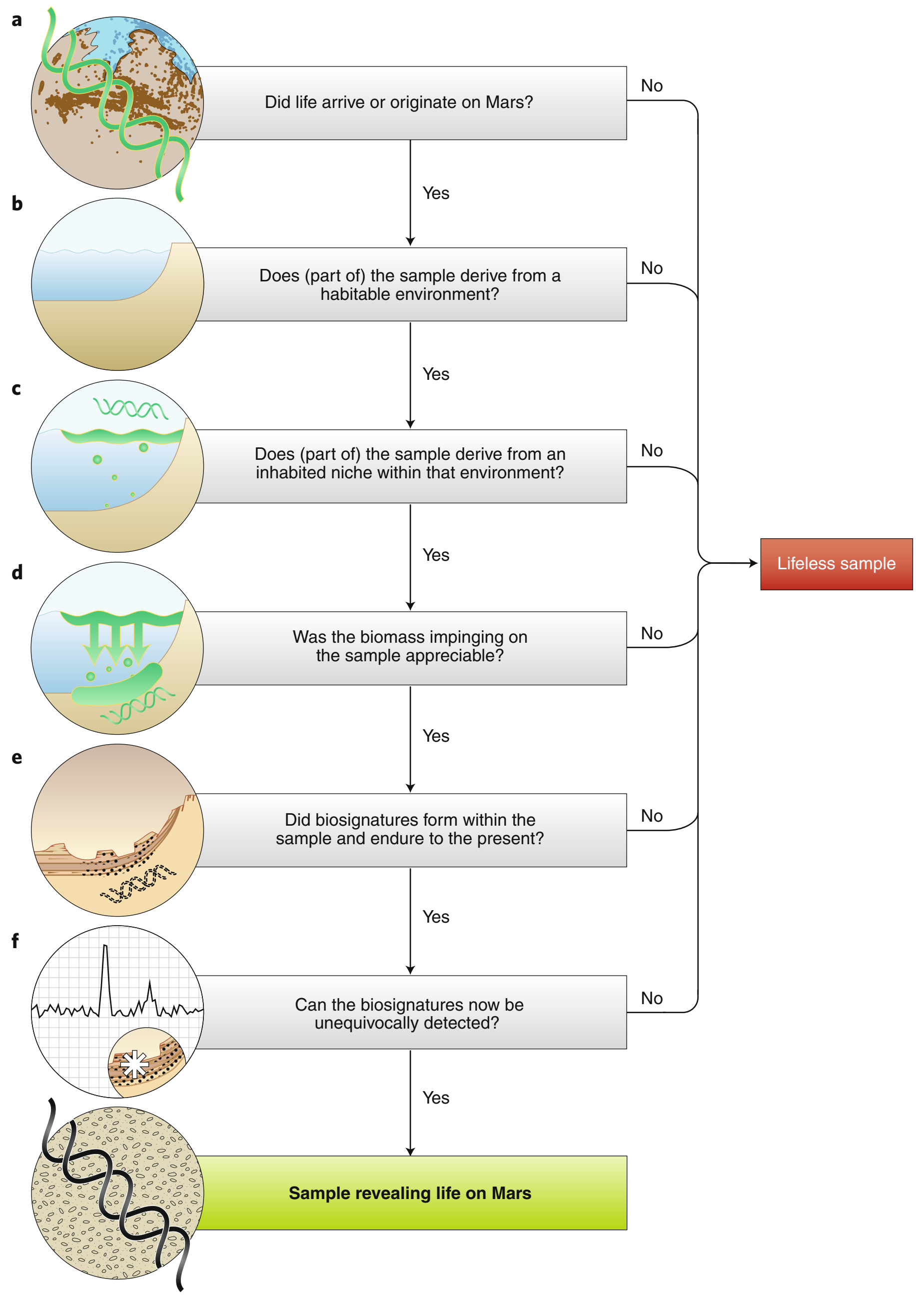

Fig. 1 | Scenarios leading to the recovery of lifeless samples from Mars. a–f, The diagram shows the progression of factors that would lead to the recovery of samples lacking signatures of life.

because of insufficient hydrological circulation or an inclement atmosphere that restricted transport of viable organisms, resulting in a situation that is rare on the Earth: habitable, but uninhabited samples[10] (Fig. 1c); (3) Attenuated trajectories of microbial evolution left certain ecological niches (for example, those requiring photosynthesis) unoccupied (Fig. 1c), leading to samples that theoretically are habitable to known metabolisms on Earth, but unoccupied on Mars; or (4) The amount of biomass interacting with the sample was too low to produce any lasting signature (Fig. 1d).

These theoretical scenarios could eventually be disentangled with empirical data. Scenario 1 could be investigated for any given sample by studying the habitable potential of the sample through laboratory analysis that could determine the content and availability of CHNOPS elements (including organic molecules), energy sources, chemical toxicity, and other physical and chemical characteristics of the microenvironment recorded by the sample. If the sample could be shown to be permissive for certain types of known life, then scenario 1 could be discounted.

Scenarios 2 and 3 could be tested by collecting samples from similar environments elsewhere on Mars, showing that they were habitable and determining whether they contain evidence of life. The sample set would allow an assessment of whether the sample under investigation represents a specific instance where there was a lack of colonization (scenario 2). If evidence was found that life did inhabit some ecological niches on Mars, but not the niche(s) represented by the sample, then scenario 3 could be suggested.

Scenario 4 could be tested by sampling the vicinity of the lifeless sample to investigate possible local heterogeneities in biomass.

Poor preservation

Even samples that did contain or interact with appreciable biomass might still be rendered apparently lifeless. The potential of Martian environments to preserve stable and enduring biosignatures is poorly known[17,18]. Processes that influence the long-term preservation of organic remains (collectively 'taphonomic' processes) on Mars are likely to differ from Earth's because of several Mars-specific factors: a lack of tectonic subsidence or burial, a more iron-rich crust, the presence of high concentrations of oxidizing agents such as perchlorates, and a tendency towards acidic fluid chemistries and lower temperatures.

A thriving ecosystem that produced no biomarkers capable of long-term preservation under the particular taphonomic conditions of Mars could lead to lifeless samples (Fig. 1e). However, it is unlikely that taphonomic conditions would be inappropriate for successful preservation on a planetary scale. In many respects, Mars offers better prospects for the preservation of multi-billion-year-old rocks than Earth[19]. Thus, the collection of many lifeless samples recording environments with diverse, taphonomically favourable conditions would strongly suggest that no such ecosystem existed. More in-depth studies and experiments are required to identify the Martian (paleo)environments most favourable to biosignature preservation[19], keeping in mind that environments that can theoretically support maximum biomass are not necessarily those where the preservation potential is maximized.

A more likely scenario is that potential signatures of life might be equivocal, ambiguous or close to detection limits

(Fig. 1f). Such samples might be considered lifeless by some workers and not by others. The debate on the biogenicity of features observed in Martian meteorite ALH84001[20] shows the clear potential for this situation to arise. Similar arguments for and against biogenicity are advanced for some features of terrestrial rocks; for example, about whether microtubules observed in some basaltic glass are the result of microbial activity or not[21].

The possibility of ambiguity should be minimized as far as possible by continuing research on the conditions that lead to false positive signatures of life, for example laboratory investigations on how biomorphic features can be formed in rocks by abiotic chemical reactions under specific Martian geochemical conditions. The further development of integrated multi-proxy approaches to biosignature detection in Martian analogue rocks will improve our ability to distinguish biogenic features from non-biological false positives[22].

Lessons for Martian sampling

Although Mars sample return and rover missions are strongly focused on finding evidence for life, lifeless samples returned from Mars will yield important constraints on the extent of habitable conditions and whether those environments were inhabited. The scenarios discussed here show that it is critical to acquire many samples. Multiple samples must be obtained from each locality, from similar (paleo)environments elsewhere across Mars, and from different potentially habitable environments in multiple locations across Mars for the scenarios presented here to be disentangled and the reasons for lifeless samples ascertained.

Like Russell's allegorical teapot, it may never be possible to show definitively that there was no isolated biota anywhere on Mars at any time; nevertheless, multiple lifeless samples from several geographical locations on Mars taken from distinct habitable paleoenvironments (for example, lacustrine clays, playa evaporitic deposits, hot spring silica sinters, or mineralized subsurface hydrothermal systems), would increase the subjective probability of this hypothesis (unless and until evidence of life on Mars is found). A Bayesian approach could be used to quantify such an increase.

If extant or extinct life was eventually to be found on Mars, it would be an important scientific advance. However, the mapping of lifeless samples, either uninhabitable samples, or habitable but lifeless samples, would remain essential to determine how that biosphere was restricted spatially, temporally or evolutionarily. Thus, an effort to map lifeless samples, which seems of limited interest to ecologists on a biologically fecund Earth, would be an activity of great importance on the environmentally more extreme Mars.

We recommend that researchers preparing for the analysis of Martian samples should place more emphasis on distinguishing different scenarios that lead to lifeless samples as opposed to a single-minded search for biosignatures. Sample collection strategies for Mars exploration would benefit from being designed around the collection of a sufficient number and diversity of samples to understand the factors that give rise to lifeless samples. ❐

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