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PERSPECTIVE
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The Martian subsurface as a potential window into the origin of life

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Few traces of Earth's geologic record are preserved from the time of life's emergence, over 3,800 million years ago. Consequently, what little we understand about abiogenesis — the origin of life on Earth — is based primarily on laboratory experiments and theory. The best geological lens for understanding early Earth might actually come from Mars, a planet with a crust that's overall far more ancient than our own. On Earth, surface sedimentary environments are thought to best preserve evidence of ancient life, but this is mostly because our planet has been dominated by high photosynthetic biomass production at the surface for the last ~2,500 million years or more. By the time oxygenic photosynthesis evolved on Earth, Mars had been a hyperarid, frozen desert with a surface bombarded by high-energy solar and cosmic radiation for more than a billion years, and as a result, photosynthetic surface life may never have occurred on Mars. Therefore, one must question whether searching for evidence of life in Martian surface sediments is the best strategy. This Perspective explores the possibility that the abundant hydrothermal environments on Mars might provide more valuable insights into life's origins.

Following planetary accretion, early delivery via impact of extra-terrestrial materials and their payload of volatiles and organic matter may have provided a vast amount of exogenous raw ingredients for abiogenesis[1]. Although the details of the post-accretionary impact period[2] are intensely debated, consensus is that large impacts were relatively common in the early inner Solar System. The catastrophic effects of the impact events would have been a major impediment to the formation, evolution and preservation of early life, particularly surface life[3]. Yet, merely 800 Myr after the Earth/Moon formed — at the time that the impact rate seems to have diminished — some manner of microbial life appears to have existed[4].

Hints of early life on Earth are found as isotopically light graphitized carbon captured in metamorphic rocks representing the ancient seafloor in what is now Greenland[5], and conical stromatolite-like structures within slightly younger rocks[6]. Cryptic evidence in the form of graphite trapped in zircons from the Jack Hills region could push life's origins even earlier into the Hadean eon[7]. These remnants of the Archaean and Hadean eons that are so relevant to understanding the temporal and taphonomic window for life's emergence comprise only about ~0.001 vol% of the terrestrial crust[8] and have been thermally and chemically altered due to their long crustal residence times.

Because the Earth's early geologic record is so poorly preserved, our limited understanding of how early organic chemistry may have assembled the building blocks of life is largely based upon laboratory experiments[9–14]. But definitive clues to the chemical steps leading to life's origins probably require empirical evidence. The fundamental question of how abiogenesis occurred on Earth may only be answerable through finding better-preserved 'cradle of life' chemical systems beyond Earth. Indeed, this question of how life originates is one of the fundamental drivers of international space exploration.

Which objects beyond Earth could potentially unlock the mystery of abiogenesis? Europa and Enceladus are high priority targets because they probably contain subsurface oceans even today[15,16]. Yet, it is not simply a subsurface ocean itself that is intriguing in terms of the origin-of-life perspective — it is the reaction between fluids and silicate rocks at the ocean–silicate interface[17] that might hold promise for energetic pathways for chemotrophic life forms[18]. However, all of the icy satellites are far from Earth and access to subsurface fluids will either require deep drilling, or we will be limited to collection of ejected molecules from transient cryo-volcanism[19,20], which may not sample fluids from the deep rock–water interface of primary interest. In addition, there is a growing interest in the possibility that terrestrial life originated not within an ocean environment but rather in vapour-dominated inland geothermal systems, where shallow pools of fluid may have interacted with porous silicate minerals and metal sulfides[21,22]. Although the icy worlds are clearly a high-priority target for understanding abiogenesis, Mars is the only Solar System object with an ancient, preserved, accessible crust containing clear evidence of water–rock reactions dating to the time when life appeared on Earth (Fig. 1).

Mars as a Rosetta Stone for early Earth

Mars, a planet without plate tectonics and with much lower weathering rates through most of its history[23], contains a much older and better-preserved geologic record than Earth (Fig. 2). At only ~10% of Earth's mass, Mars began with far less primordial and

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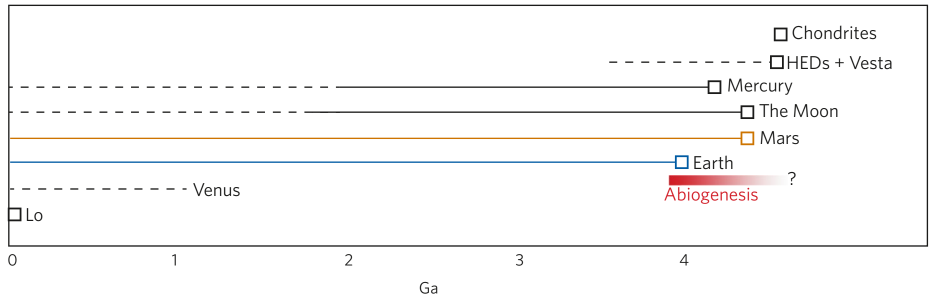

Fig. 1 | A comparison of the age of planetary crust. Lines represent the best estimate limits of oldest preserved crust and dashed lines represent significant uncertainties. The crust of Mars might provide the best window into the time when abiogenesis occurred on Earth. See Methods for explanation of data included in the graph. HED, Howardite–eucrite–diogenite.

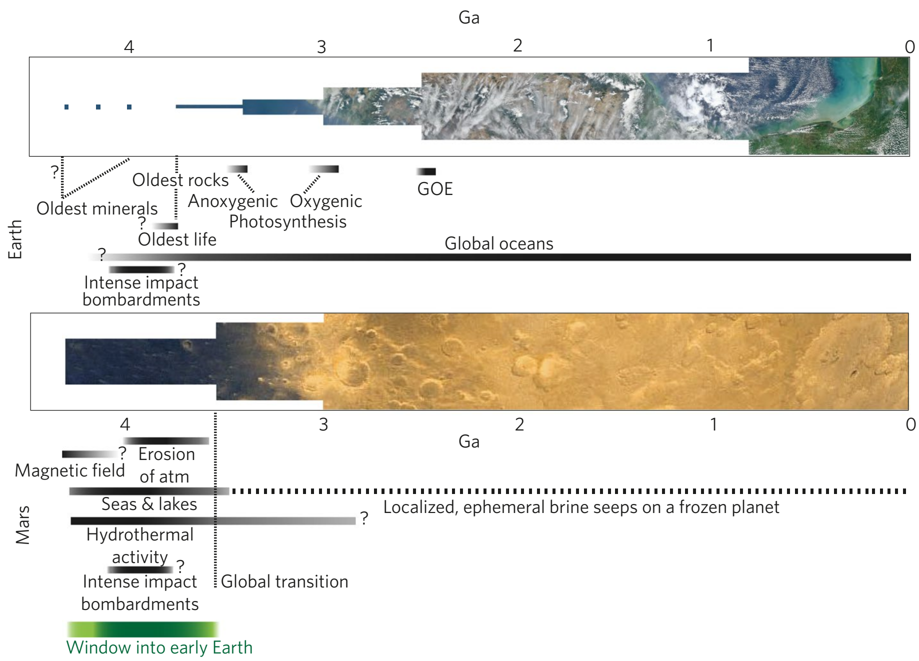

Fig. 2 | A comparison of key events in the histories of the Earth and Mars. The area of each timeline is an approximation of the amount of crust preserved over different epochs (refs [1–8]). The generally unmetamorphosed and well-preserved geologic record of early Mars may be an invaluable window into the geology and prebiotic chemistry of the early Earth. GOE, Great Oxygenation Event; atm, atmosphere. Image credit: NASA.

radiogenic heat[24]. By approximately 4,000 million years ago (Ma), Mars had cooled sufficiently to cause cessation of the magnetic dynamo[25]. The loss of the Martian magnetic field marked the timing of its clearest divergence from the evolution of the Earth and its biosphere. It exposed the Martian surface to punishing radiation[26], and the atmosphere began to be sputtered away by solar wind[27].

Mars may have been cold, arid, oxidizing and generally inhospitable at the surface for much of its history; however, hydrothermal conditions in the near surface or subsurface might have been considerably more clement. Infrared remote sensing has revealed the presence of thousands of deposits of hydrated silicate minerals as well as various salts throughout the Martian surface[28]. Although essentially all of the salts and some of the hydrated silicates seemingly formed in surface environments during what may have been short-lived climate excursions[29], many of the deposits represent materials that were seemingly exhumed from the subsurface[30]. Among the exhumed phases are serpentines, Fe- and Mg-rich smectite clays, chlorites, carbonates and amorphous silica that seemingly indicate widespread subsurface hydrothermal alteration (Fig. 3).

In 2008, the Spirit Rover also stumbled upon soils and bedrock of nearly pure opaline silica (>90 wt% SiO_2) in the vicinity of Home Plate in Gusev crater[31] providing compelling evidence for fumarolic hydrothermal activity. Similar materials were also detected in at least one younger caldera, that on Nili Patera[32].

It is difficult to strongly constrain the timing of near surface and deep subsurface hydrothermal alteration on Mars other than to state that it was primarily in the Noachian[30] (>3,600 Ma). Whereas some studies document impact-induced hydrothermal activity in Hesperian crater deposits (3,000–3,600 Ma); for example[33], there is little to no evidence for similar alteration in craters formed in Amazonian age terranes[34] (<3,000 Ma) (Fig. 3).

The subsurface — from metres to kilometres in depth — is potentially the largest, longest-lived and most stable habitable environment on Mars[35]. A significant fraction of Earth's biomass consists of prokaryotic microbial life in a deep biosphere[36], a habitat that was essentially disregarded more than 30 years ago and remains largely unexplored today[37]. Subsurface lithoautotrophic microbial ecosystems (SLiMEs) that appear to dominate fractured basaltic and granitic aquifers rely upon primary production from

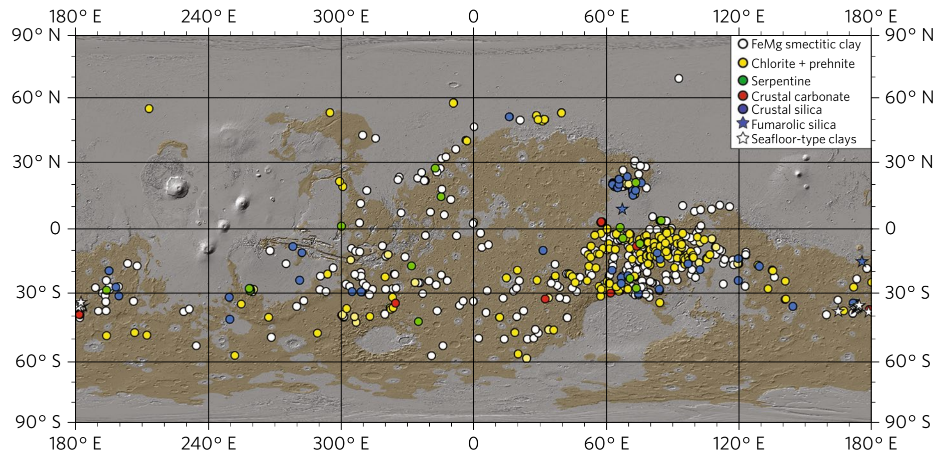

Fig. 3 | Hydrothermal and exhumed, altered subsurface deposits on Mars. The global occurrence of alteration minerals formed in deep crustal or surface hydrothermal environments detected by infrared remote sensing. See Methods for explanation of data included in the map.

H_2-oxidizing- and CO_2-reducing- methanogens and acetogens[38,39]. The life-sustaining H_2 has been shown to be generated through abiotic hydrolysis of ferrous minerals in basalt[38] and ultramafic rock (for example, serpentinization)[40] and through radiolysis of water[41]. Other potential sources of H_2 include exsolved gases from basaltic magmas, decomposition of CH_4 at $T > 600$ °C, reactions between CH_4, H_2O and CO_2 at elevated temperatures and silicate cataclasis. Just as important, radiolysis has been shown to generate electron acceptors such as sulfate along with H_2, which can be utilized to sustain sulphate reducing bacteria indefinitely[38].

On Earth, the extent of the deep biosphere is controlled not only by energy sources and nutrients, but by availability of pore space. Although porosity is strongly dependent on rock type, continental rocks typically have <1–5% porosity at depth of 3–4 km. But due to the lower gravity on Mars the rocks are less compacted; similar values of porosity extend to ~10 km depth[42].

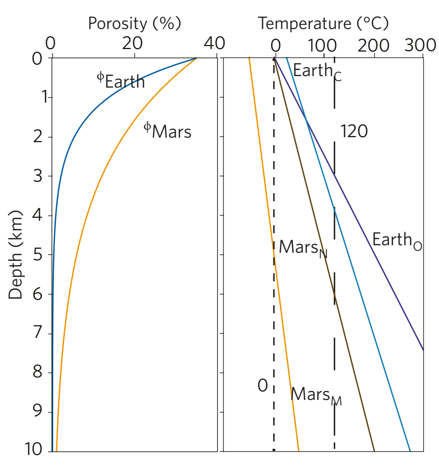

Fig. 4 | A comparison of the average porosity and thermal gradients of the crusts of Earth and Mars. For similar rock types and surface porosities, the Martian crust contains significantly more porosity to greater depth than that of the Earth (left). Estimated thermal gradients for Noachian (N) and modern (M) Mars are lower than that of the modern continental (C) or oceanic (O) crust of Earth (right). A hypothetical 120 °C limit is encountered at 3–4 km depth on Earth, where the porosity is 1–2%. The same temperature limit would not be encountered until ~6 km depth on Noachian Mars or much deeper on modern Mars. See Methods for explanation of data included in the graph.

Although heat flow in the terrestrial crust is heterogeneous, geothermal gradients (10–40 K km^{-1}) in continental and oceanic crustal settings suggest that the terrestrial deep biosphere likely does not extend past ~3–4 km depth, beyond which the most tolerant hyperthermophiles are no longer viable (~120 °C)[43]. However, on Mars the lower surface temperature and lower crustal heat flow add up to a more favourable thermal regime within the crust. Assuming a thermal gradient of 20 K km^{-1} on Noachian Mars, the 120 °C temperature limit would not have been reached until nearly twice the depth where it occurs on Earth (Fig. 4).

Most of the Martian crust is ultramafic or mafic, and probably contains interlayered volcanics and impactites. Given the lower temperature gradient on Mars compared to Earth, it is likely that Lost-City-type[44] (low-temperature, alkaline) serpentinization reactions[18] occurred over a large range of depths on Mars, producing bioavailable H_2 (ref. [45]). Although this mafic-rich crust is less radiogenic that average Earth continental crust, H_2 production rates from radiolysis should be as great as that for subsurface environments on the Earth because of the greater porosity of the Martian subsurface[46]. Exhumed subsurface carbonates, and the presence of vein carbonates in Martian meteorites exhumed from the subsurface[47] suggest that these reactions happened in the presence of CO_2 and may have produced abiogenic hydrocarbons. Consequently, the subsurface habitable volume and abiotic energy sources probably would have been as readily available, if not more so, on Mars as on Earth.

It is probable that fluids within alkaline crustal hydrothermal systems would have mixed with descending acidic, sulfur- (H_2S, SO_2) and CO_2-rich fluids from surface and near-surface environments through taliks, areas of unfrozen ground surrounded by permafrost[42]. Likewise, alkaline fluids might have emerged in deep basins and interfaced with acidic lakes and meltwater from acidic ice deposits, resulting in mixing scenarios that may have been a source of redox energy[18,48]. A test for such an origin-of-life scenario would be invaluable to earth and planetary scientists alike.

Dim prospects for surface life on Mars

The evolutionary innovation of oxygenic photosynthesis by cyanobacteria was a turning point in the history of life on Earth[49]. Although the timing remains controversial, oxygenic photosynthesis appeared late within cyanobacterial evolution[50], well after their divergence at 2.5 to 2.6 billion years ago (Ga)[51] and after the rise of its evolutionary precursor, Mn-oxidizing phototrophy[52] and before the Great Oxidation Event at 2.3–2.45 Ga[53,54]. Production of atmospheric O_2 led to the formation of ozone, which shielded the immediate surface zone from harmful UV rays. The success of cyanobacteria not only led to marked increases in biomass production and deposition in shallow water environments (shelf, coastal marine and lacustrine) where high sedimentary rates prevail, but also to the colonization of arid and cold surface environments by endolithic communities[55]. Our palaeontologic record over the last ~3000 My is dominated by carbonaceous sedimentary rocks from such environments[56].

On Mars, there may have never been an evolutionary drive to inhabit the surface. During the Noachian, Mars was most likely cold, arid and oxidizing[57,58]. Fluvial channels and most crater lakes on Noachian Mars once thought to have required some form of greenhouse atmosphere in order to stabilize liquid water over geologic time-scales, are now considered by some to have formed within thousands of years[59,60], perhaps under a tenuous atmosphere in the Noachian. The surface seemingly shifted from a cold but episodically wet landscape to a frozen, hyperarid desert at the Noachian–Hesperian transition approximately 3,600 Ma[61].

The success of surface life on Earth can be traced back to the evolution of oxygenic photosynthesis in the Archean. The most recent molecular clocks have placed the origin of photosynthesis at ~3,000 Ma, and the origin of oxygenic photosynthesis later than 2,500–2,600 Ma on Earth. Martian phototrophs would have had to attain these evolutionary benchmarks by 3,600 Ma, despite the generally frozen and arid surface conditions, fainter sunlight and the intense radiation flux from solar UV, solar energetic particles and galactic cosmic rays. By contrast, the evolution of methanogenesis, an important metabolic pathway for subsurface life, occurred prior to the divergence of Euryarchaeota and Crenarchaeota and represents one of the most ancient forms of metabolism[62].

Considering these challenges, it seems prudent to consider the possibility that photosynthesis never evolved on Mars. Unless high-energy radiation could be harnessed as a form of energy, as has been reported for certain fungal species[63], the radiated surface environment is an impediment to the existence of surface life and an obstacle for the preservation of organic materials[35]. With all of this in mind, it seems time to reconsider the current Mars exploration philosophy.

A Mars exploration strategy focused on abiogenesis

Much of the thinking about candidate landing sites for future landed missions has been aimed at maximizing taphonomic potential by targeting sedimentary environments such as lacustrine delta deposits. Although this Mars exploration strategy is understandable, such an approach suffers a major epistemological problem: Mars is not Earth. We must recognize that our entire perspective on how life has evolved and how evidence of life is preserved is coloured by the fact that we live on a planet where photosynthesis evolved. Even if photosynthesis did evolve on Mars, questions remain as to how successful surface life would have been, and whether evidence of that life could have been captured in the sedimentary record.

Considering that some of the most ancient analogue habitats on Earth, hydrothermal and subsurface environments, are mirrored on Mars, it is logical to search for the signs of primitive life there in settings analogous to where it may have emerged here. We thereby not only maximize our chances of finding chemotrophic life, but also of finding the evidence of prebiotic chemistry that might have led to the formation of life in a sustained habitable setting.

It should be noted that a significant fraction of the biomass and biosignatures associated with surface silica sinters on Earth, similar to the type found in Gusev crater[31], correspond to photosynthetic bacteria that thrive in fluid mixing zones[64]. Deep in the past, in the absence of photosynthesis, chemotrophs may have dominated these systems. Nevertheless, care should be taken in evaluating the preservation potential for textural and chemical biomarkers in this context.

Potential biosignatures in exhumed deep crustal rocks include the following: (1) isotopic signatures of gasses (for example, CH_4) trapped in fluid inclusions; (2) isotopic signatures of minerals, fluids and organic matter trapped in veins and diagenetic replacements[65]; (3) metal or carbonate accumulations at redox gradients — especially indicating disequilibrium conditions; (4) biotextures in fractures and pores; (5) microfossils preserved in mineralized veins[65] or diagenetic cements and concretions; and (6) important organic molecules such as nucleic acids, lipids and amino acids in fractures, fluid inclusions and within mineral aggregates[66,67]. The detection of disequilibrium chemistry implicating life may perhaps be less satisfying than the detection of fossilized microbial mats in lacustrine sediments, but such an approach might actually teach us more about the origin of life. Because the chemical signatures from the dawn of life have been entirely obliterated on Earth, finding these clues on Mars, a unique site within the Solar System, would provide an invaluable window into our own history.

Given how little we understand about the origin of life on Earth, it makes sense to adopt a broader plan to seek signs of life. In other words, it is perhaps more logical to seek evidence of prebiotic chemistry that might have led to the formation of life in sustained habitable settings rather than searching directly for evolved forms of surface life in ephemeral environments. We could search for the signs of primitive life on Mars in settings analogous to where it may have formed on Earth.

Although concerns about the preservation potential of biosignatures in rocks from hydrothermal and subsurface Martian environments are important to consider, it is clear that preservation potential does not present an ultimate stumbling block. The preservation of biomolecules associated with hydrothermal activity in the extra-terrestrial context has been validated by their common occurrence in hydrous meteorites with signs of ancient hydrothermal processing ($\leq$150 °C)[68]. Upon the cessation of the hydrothermal event, plunging temperatures in Martian environments would be ideal for preserving biosignatures (for example, amino acid enantiomeric ratio)[69]. Silica has been recognized for its significance in microfossil preservation, and iron-silicate biomineralization in hot spring environments has been shown to serve as a potent shield to UV radiation[70]. Biomarker preservation in subsurface environments is a field that has hardly been explored, but biomarkers from Cretaceous subsurface environments clearly demonstrate that preservation is possible[66].

By focusing our search on non-photosynthetic life, we maximize our chances of not only finding biosignatures on Mars but also uncovering clues to abiogenesis, an aspect that should be a key part of our exploration strategy. The quest to understand life's origins could be described as: 'follow the energy sources[45]: sulfur, iron and H_2'. That mantra would lead us to Mars, an iron and sulfur-rich planetary crust with abundant evidence for ancient hydrothermal activity and H_2 production that could have fuelled an early chemosynthetic biosphere.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Competing interests

The authors declare no competing financial interests.

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Methods

Age estimates of the crusts of Solar System objects were based on data from ref. [71]. Exact ages of rock units are largely unknown. But, crater counting statistics across Solar System objects provide a reliable basis for comparison and absolute ages derived from meteorites provide strong constraints and tie points.The map of hydrothermal and subsurface mineral deposits on Mars (Fig. 3) was derived from multiple sources. The primary data sources include mineral detections[28,30], which were created with significant input from the science instrument teams for the Observatoire pour la minéralogie, l'eau, les glaces et l'activité (OMEGA)[72] and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)[73]. These instruments have produced thousands of detections of hydrated minerals on Mars, many of which correspond to contexts in surface environments and many of which correspond to deposits exhumed from the subsurface. All of the detections shown in Fig. 3 correspond to detections that have seemingly been exhumed from the subsurface by impact or erosion.

The edited global-scale datasets of Carter and Ehlmann[28,30] were supplemented with other information pertaining to the detection of subsurface, surface or near-surface hydrothermal deposits. Subsurface carbonate detections were supplemented with data from studies of exhumed carbonates[74] and a global carbonate[75] study. Serpentine deposits include those described in a global search for serpentinized rocks[76]. Fumarolic silica corresponds to silica detected by the Spirit rover[77] and with CRISM. Seafloor-type clays correspond to Fe- and Mg-rich phyllosilicates and carbonates with in the Eridania basin on Mars, which was the site of a large inland sea when the deposits formed >3,800 Ma (ref. [78]).

The values in Fig. 4 were based on a few inputs. First, generally accepted knowledge suggests that a geothermal gradient of 25 °C is plausible for continental settings. A range of higher gradients of 30–40 °C is adopted for oceanic settings. 'Surface' temperatures of 0 °C and 25 °C are adopted for seafloor and continental settings, respectively. Estimates of Martian geothermal gradients are based on geophysical data[79] suggesting a thermal gradient of 20 °C is reasonable for the Noachian and 10 °C is reasonable for Amazonian Mars.

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