The search for clues to abiogenesis on Mars

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[First Paragraph]

Few traces of Earth's geologic record are preserved from the time of life's emergence, over 3800 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 the 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 ~2500 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 paper explores the possibility that the abundant hydrothermal environments on Mars might provide more valuable insights into life's origins.

[main text]

Following planetary accretion, early delivery via impact of extraterrestrial 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 termed the "Late Heavy Bombardment[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 a mere 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 Canada[5] and Greenland[6], and conical stromatolite-like structures within slightly younger rocks[7]. 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[8]. These remnants of the Archean 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[9] and have been intensely 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[10–15]. 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 likely contain subsurface oceans even today[16],[17]. 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[18] that might hold promise for energetic pathways for chemotrophic life forms[19]. 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[20],[21], 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 sulphides[22,23]. While 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 (Figure 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[24], contains a much older and better-preserved geologic record than the Earth

(Figure 2). At only ~10% of Earth's mass, Mars began with far less primordial and radiogenic heat[25]. By about 4000 Mya, Mars had cooled sufficiently to cause cessation of the magnetic dynamo[26]. 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[27], and the atmosphere began to be sputtered away by solar wind[28].

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[29]. While 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[30], many of the deposits represent materials that were seemingly exhumed from the subsurface[31]. Among the exhumed phases are serpentines, Fe and Mg-rich smectite clays, chlorites, carbonates, and amorphous silica that seemingly indicate widespread subsurface hydrothermal alteration (Figure 3).

In 2008, the Spirit Rover also stumbled upon soils of nearly pure opaline silica (>90 wt % SiO_2) in the vicinity of Home Plate in Gusev crater[32] providing compelling evidence for fumarolic hydrothermal activity. Similar materials were also detected in at least one younger caldera, that on Nili Patera[33].

It is difficult to strongly constrain the timing of near surface and deep subsurface hydrothermal alteration other than to state that it was primarily in the Noachian (>3600 Mya)[31]. Whereas some studies document impact-induced hydrothermal activity in Hesperian crater deposits (3000-3600 Mya) e.g.[34], there is little to no evidence for similar alteration in craters formed in Amazonian age terranes[35] (<3000 Mya) (Figure 3).

The subsurface – from metres to kilometres depth - is potentially the largest, longest-lived, and most stable habitable environment on Mars[36]. A significant fraction of Earth's biomass consists of prokaryotic microbial life in a deep biosphere[37], a habitat that was essentially disregarded more than 30 years ago and remains largely unexplored today[38]. The primary producers in deep subsurface ecosystems are anaerobic chemoautotrophs, or SLiMEs, that oxidize H_2 and reduce CO_2 to produce CH_4 (i.e. methanogens) and acetate (i.e. acetogens)[39,40]. The life-sustaining H_2 has been shown to be generated through abiotic hydrolysis of ferrous minerals in basalt[41] and ultramafic rock (e.g. serpentinization)[42] and through radiolysis of water[49]. Other potential sources of H_2 include exsolved gases from basaltic magmas, decomposition of CH_4 at T > 600ºC, 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 sulphate along with H_2, which can be utilized to sustain sulphate reducing bacteria indefinitely[43].

On Earth, the extent of the deep biosphere is controlled not only by energy sources and nutrients, but by availability of pore space. While 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 in depth[44].

Although heat flow in the terrestrial crust is heterogeneous, geothermal gradients (10-40 K/km) in continental and oceanic crustal settings suggest that the terrestrial deep biosphere likely does not extend passed ~3-4 km depth, beyond which the most tolerant thermophiles are no longer viable (~120°C)[41]. 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 on Noachian Mars, the 120°C temperature limit would not have been reached until nearly twice the depth where it occurs on Earth (Figure 4).

Most of the martian crust is ultramafic or mafic, and likely contains interlayered volcanics and impactites. Given the lower temperature gradient on Mars compared to Earth, it is likely that Lost City-type[45] (low-temperature, alkaline) serpentinization reactions[19] occurred over a large range of depths on Mars, producing bioavailable H_2[46]. 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[47]. Exhumed subsurface carbonates, and the presence of vein carbonates in martian meteorites exhumed from the subsurface[48] 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 would likely 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, sulphur- (H_2S, SO_2) and CO_2-rich fluids from surface and near-surface environments through taliks, areas of unfrozen ground surrounded by permafrost[44]. Likewise, alkaline fluids might have emerged in deep basins and interfaced with acidic lakes and meltwater from acidic ice deposits, resulting in mixing scenarios which may have been a source of redox energy[19,49]. 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[50]. Although the timing remains controversial, oxygenic photosynthesis appeared late within cyanobacterial evolution[51], well after their divergence at 2.5 to 2.6 billion years[52] and after the rise of its evolutionary precursor, Mn-oxidizing phototrophy[53] and before the Great Oxidation Event at 2.3-2.45 Ga[54,55]. 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[56]. Our paleontologic record over the last ~3000 Mya is dominated by carbonaceous sedimentary rocks from such environments[57].

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[58,59]. 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[60,61], 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 ca. 3600 Mya[62].

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 ~3000 Myr and the origin of oxygenic photosynthesis later than 2500 to 2600 Mya on Earth. Martian phototrophs would have had to attain these evolutionary benchmarks by 3600 Mya, despite the generally frozen and arid surface conditions, fainter sunlight, and the intense radiation flux from solar UV, Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). By contrast, the evolution of methanogenesis, an important metabolic pathway for subsurface life, occurred prior to the divergence of Euryarcheota and Crenarcheota and represents one of the most ancient forms of metabolism[63].

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[64], the radiated surface environment is an impediment to the existence of surface life and an obstacle for the preservation of organic materials[36]. With all 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. While 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 colored 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.

The search for biosignatures in hydrothermal deposits must also be questioned. For example, silica sinter deposits of the type found in Gusev crater[32] are widely considered deposits with high preservation potential for textural and chemical biomarkers on Earth. But, a significant fraction of the biomass and biosignatures associated with silica sinters correspond to photosynthetic bacteria that thrive in fluid mixing zones[65] and therefore the effects of a possible absence of photosynthesis on biosignature preservation should also be considered in this context.

Potential biosignatures in exhumed deep crustal rocks include the following: 1) isotopic signatures of gasses (e.g. CH_4) trapped in fluid inclusions, 2) isotopic signatures of minerals, fluids and organic matter trapped in veins and diagenetic replacements[66], 3) metal or carbonate accumulations at redox gradients—especially indicating disequilibrium conditions, 4) biotextures in fractures and pores, 5) microfossils preserved in mineralized veins[66] 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[67,68]. 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.

While 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 extraterrestrial context has been validated by their common occurrence in hydrous meteorites with signs of ancient hydrothermal processing ($\leq$150°C)[69]. Upon the cessation of the hydrothermal event, plunging temperatures in martian environment would be ideal for preserving biosignatures (e.g. amino acid enantiomeric ratio)[70]. 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[71]. 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[67].

By focusing our search on non-photosynthetic life, we not only maximize our chances of 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[46]: sulphur, iron and H_2." That mantra would lead us to Mars, an iron and sulphur-rich planetary crust with abundant evidence for ancient hydrothermal activity and H_2 production that could have fuelled an early chemosynthetic biosphere.

Methods

The map of hydrothermal and subsurface mineral deposits on Mars (Figure 3) was derived from multiple sources. The primary data sources include mineral detections by Carter et al.[29] and Ehlmann et al.[31], 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 1000s 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 Figure 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 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 >3800 Mya[78].

Figure Captions:

Figure 1: A comparison of the age of planetary crust. Lines represent the best estimate limits of oldest preserved crust. Dashed lines represent significant uncertainties. The crust of Mars might provide the best window into the time when abiogenesis occurred on Earth.

Figure 2: A comparison of key events in the histories of the Earth and Mars. The area of each time line is an approximation of the amount of crust preserved from over different epochs. The generally unmetamorphosed and well-preserved geologic record of early Mars is an invaluable window into the geology and prebiotic chemistry of the early Earth.

Figure 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.

Figure 4: A comparison of the average porosity of 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 (ϕ_N) and modern (ϕ_m) Mars are lower than that of the modern continental (ϕ_c) or oceanic (ϕ_o) crust of Earth (right). A hypothetical 120ºC 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.

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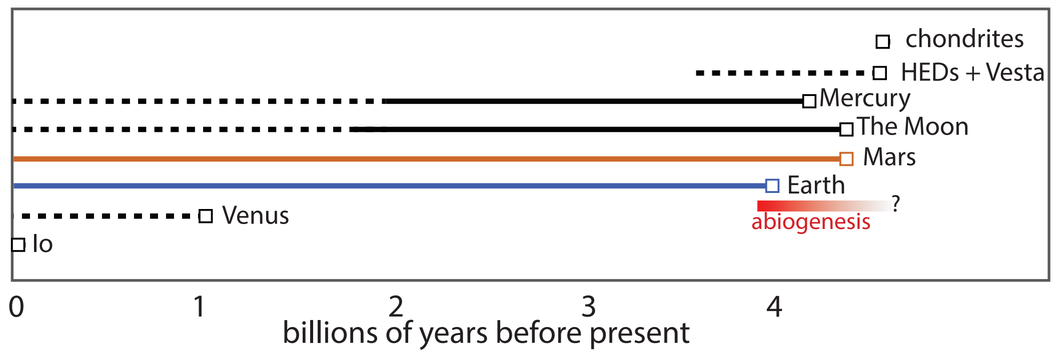
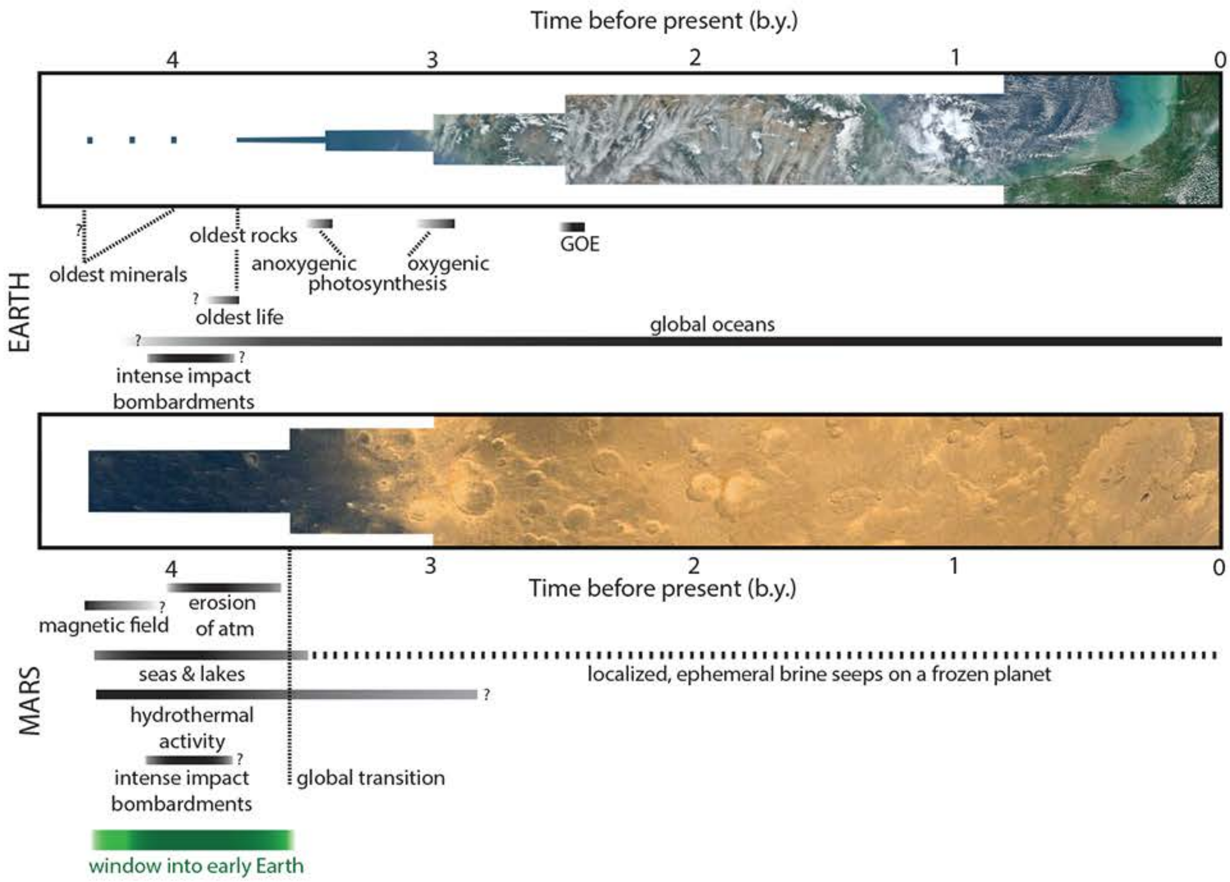
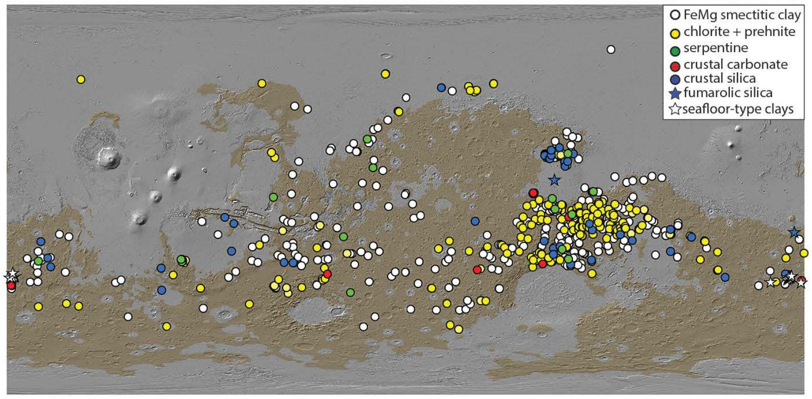
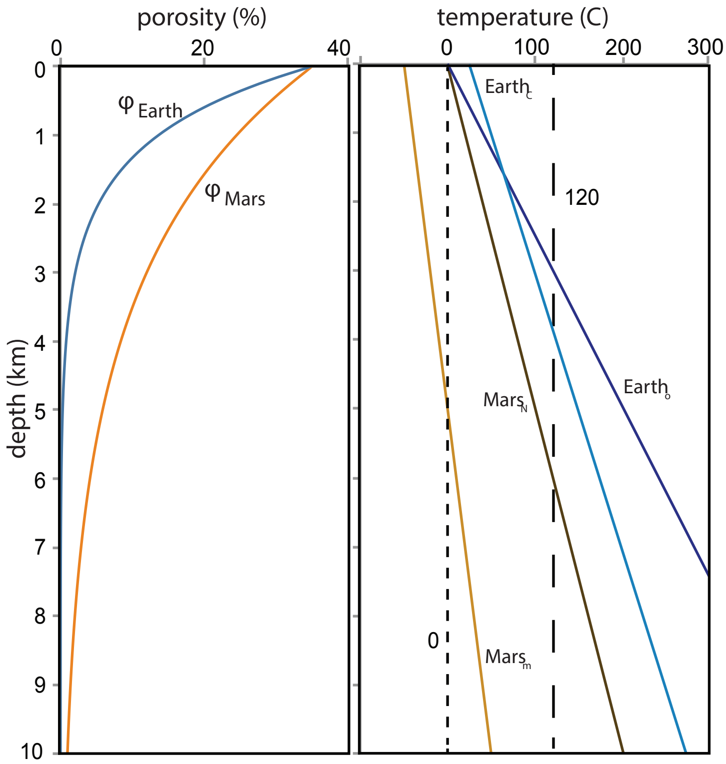

chondrites
HEDs + Vesta
Mercury
The Moon
Mars
Earth
?
abiogenesis
Venus
Io
0
1
2
3
4
billions of years before present


Time before present (b.y.)
4
3
2
1
0
EARTH
oldest minerals
oldest rocks
anoxygenic
oxygenic
photosynthesis
GOE
oldest life
global oceans
intense impact
bombardments
MARS
Time before present (b.y.)
magnetic field
erosion
of atm
seas & lakes
localized, ephemeral brine seeps on a frozen planet
hydrothermal
activity
intense impact
bombardments
global transition
window into early Earth


FeMg smectitic clay
chlorite + prehnite
serpentine
crustal carbonate
crustal silica
fumarolic silica
seafloor-type clays



porosity (%)
0
20
40
temperature (C)
0
100
200
300
depth (km)
0
1
2
3
4
5
6
7
8
9
10
φ Earth
φ Mars
Earth_C
120
Earth_o
Mars_N
0
Mars_m