The search for clues to abiogenesis on Mars

Joseph R. Michalski, University of Hong Kong

Tullis C. Onstott, Princeton University

Stephen J. Mojzsis, University of Colorado

John Mustard, Brown University

Queenie Chan, NASA Johnson Space Center

Paul B. Niles, NASA Johnson Space Center

Sarah Stewart Johnson, Georgetown University

[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].

39

40 Hints of early life on Earth are found as isotopically light graphitized carbon captured in

41 metamorphic rocks representing the ancient seafloor in what is now Canada[5] and Greenland[6],

42 and conical stromatolite-like structures within slightly younger rocks[7]. Cryptic evidence in the

43 form of graphite trapped in zircons from the Jack Hills region could push life's origins even

44 earlier into the Hadean eon[8]. These remnants of the Archean and Hadean eons that are so

45 relevant to understanding the temporal and taphonomic window for life's emergence

46 comprise only about ~0.001 vol.% of the terrestrial crust[9] and have been intensely thermally

47 and chemically altered due to their long crustal residence times.

48

49 Because the Earth's early geologic record is so poorly preserved, our limited understanding of

50 how early organic chemistry may have assembled the building blocks of life is largely based

51 upon laboratory experiments[10–15]. But definitive clues to the chemical steps leading to life's

52 origins probably require empirical evidence. The fundamental question of how abiogenesis

53 occurred on Earth may only be answerable through finding better preserved "cradle of life"

54 chemical systems beyond Earth. Indeed, this question of how life originates is one of the

55 fundamental drivers of international space exploration.

56

57 Which objects beyond Earth could potentially unlock the mystery of abiogenesis? Europa and

58 Enceladus are high priority targets because they likely contain subsurface oceans even

59 today[16,17]. Yet, it is not simply a subsurface ocean itself that is intriguing in terms of the

60 origin of life perspective—it is the reaction between fluids and silicate rocks at the ocean-

61 silicate interface[18] that might hold promise for energetic pathways for chemotrophic life

62 forms[19]. However, all of the icy satellites are far from Earth and access to subsurface fluids

63 will either require deep drilling, or we will be limited to collection of ejected molecules from

64 transient cryo-volcanism[20,21], which may not sample fluids from the deep rock-water interface

65 of primary interest. In addition, there is a growing interest in the possibility that terrestrial life

66 originated not within an ocean environment but rather in vapour-dominated inland geothermal

67 systems, where shallow pools of fluid may have interacted with porous silicate minerals and

68 metal sulphides[22,23]. While the icy worlds are clearly a high-priority target for understanding

69 abiogenesis, Mars is the only Solar System object with an ancient, preserved, accessible crust

70 containing clear evidence of water-rock reactions dating to the time when life appeared on

71 Earth (Figure 1).

72

73 **Mars as a Rosetta Stone for Early Earth**

74 Mars, a planet without plate tectonics and with much lower weathering rates through most of

75 its history[24], contains a much older and better-preserved geologic record than the Earth

76　(Figure 2). At only ~10% of Earth's mass, Mars began with far less primordial and radiogenic

77　heat[25]. By about 4000 Mya, Mars had cooled sufficiently to cause cessation of the magnetic

78　dynamo[26]. The loss of the martian magnetic field marked the timing of its clearest divergence

79　from the evolution of the Earth and its biosphere. It exposed the martian surface to punishing

80　radiation[27], and the atmosphere began to be sputtered away by solar wind[28].

81

82　Mars may have been cold, arid, oxidizing and generally inhospitable at the surface for much

83　of its history, however hydrothermal conditions in the near surface or subsurface might have

84　been considerably more clement. Infrared remote sensing has revealed the presence of

85　thousands of deposits of hydrated silicate minerals as well as various salts throughout the

86　martian surface[29]. While essentially all of the salts and some of the hydrated silicates

87　seemingly formed in surface environments during what may have been short lived climate

88　excursions[30], many of the deposits represent materials that were seemingly exhumed from the

89　subsurface[31].　Among the exhumed phases are serpentines, Fe and Mg-rich smectite clays,

90　chlorites, carbonates, and amorphous silica that seemingly indicate widespread subsurface

91　hydrothermal alteration (Figure 3).

92

93　In 2008, the Spirit Rover also stumbled upon soils of nearly pure opaline silica (>90 wt %

94　SiO_2) in the vicinity of Home Plate in Gusev crater[32] providing compelling evidence for

95　fumarolic hydrothermal activity. Similar materials were also detected in at least one younger

96　caldera, that on Nili Patera[33].

97

98　It is difficult to strongly constrain the timing of near surface and deep subsurface

99　hydrothermal alteration other than to state that it was primarily in the Noachian (>3600

100　Mya)[31]. Whereas some studies document impact-induced hydrothermal activity in Hesperian

101　crater deposits (3000-3600 Mya) e.g.[34], there is little to no evidence for similar alteration in

102　craters formed in Amazonian age terranes[35] (<3000 Mya) (Figure 3).

103

104　The subsurface – from metres to kilometres depth - is potentially the largest, longest-lived,

105　and most stable habitable environment on Mars[36]. A significant fraction of Earth's biomass

106　consists of prokaryotic microbial life in a deep biosphere[37], a habitat that was essentially

107　disregarded more than 30 years ago and remains largely unexplored today[38]. The primary

108　producers in deep subsurface ecosystems are anaerobic chemoautotrophs, or SLiMEs, that

109　oxidize H_2 and reduce CO_2 to produce CH_4 (i.e. methanogens) and acetate (i.e. acetogens)[39,40].

110　The life-sustaining H_2 has been shown to be generated through abiotic hydrolysis of ferrous

111　minerals in basalt[41] and ultramafic rock (e.g. serpentinization)[42] and through radiolysis of

112　water[49]. Other potential sources of H_2 include exsolved gases from basaltic magmas,

3

113   decomposition of CH_4 at T > 600ºC, reactions between CH_4, H_2O and CO_2 at elevated

114   temperatures and silicate cataclasis. Just as important, radiolysis has been shown to generate

115   electron acceptors such as sulphate along with H_2, which can be utilized to sustain sulphate

116   reducing bacteria indefinitely[43].

117

118   On Earth, the extent of the deep biosphere is controlled not only by energy sources and

119   nutrients, but by availability of pore space. While porosity is strongly dependent on rock type,

120   continental rocks typically have <1-5% porosity at depth of 3-4 km. But due to the lower

121   gravity on Mars the rocks are less compacted; similar values of porosity extend to ~10 km in

122   depth[44].

123

124   Although heat flow in the terrestrial crust is heterogeneous, geothermal gradients (10-40

125   K/km) in continental and oceanic crustal settings suggest that the terrestrial deep biosphere

126   likely does not extend passed ~3-4 km depth, beyond which the most tolerant thermophiles

127   are no longer viable (~120°C)[41]. However, on Mars the lower surface temperature and lower

128   crustal heat flow add up to a more favourable thermal regime within the crust. Assuming a

129   thermal gradient of 20 K/km on Noachian Mars, the 120°C temperature limit would not have

130   been reached until nearly twice the depth where it occurs on Earth (Figure 4).

131

132   Most of the martian crust is ultramafic or mafic, and likely contains interlayered volcanics

133   and impactites. Given the lower temperature gradient on Mars compared to Earth, it is likely

134   that Lost City-type[45] (low-temperature, alkaline) serpentinization reactions[19] occurred over a

135   large range of depths on Mars, producing bioavailable H_2[46]. Although this mafic-rich crust is

136   less radiogenic that average Earth continental crust, H_2 production rates from radiolysis

137   should be as great as that for subsurface environments on the Earth because of the greater

138   porosity of the martian subsurface[47]. Exhumed subsurface carbonates, and the presence of

139   vein carbonates in martian meteorites exhumed from the subsurface[48] suggest that these

140   reactions happened in the presence of CO_2 and may have produced abiogenic hydrocarbons.

141   Consequently, the subsurface habitable volume and abiotic energy sources would likely have

142   been as readily available, if not more so, on Mars as on Earth.

143

144   It is probable that fluids within alkaline crustal hydrothermal systems would have mixed with

145   descending acidic, sulphur- (H_2S, SO_2) and CO_2-rich fluids from surface and near-surface

146   environments through taliks, areas of unfrozen ground surrounded by permafrost[44]. Likewise,

147   alkaline fluids might have emerged in deep basins and interfaced with acidic lakes and

148   meltwater from acidic ice deposits, resulting in mixing scenarios which may have been a

149 source of redox energy[19,49]. A test for such an origin of life scenario would be invaluable to

150 earth and planetary scientists alike.

151

152 **Dim prospects for surface life on Mars**

153 The evolutionary innovation of oxygenic photosynthesis by cyanobacteria was a turning point

154 in the history of life on Earth[50]. Although the timing remains controversial, oxygenic

155 photosynthesis appeared late within cyanobacterial evolution[51], well after their divergence at

156 2.5 to 2.6 billion years[52] and after the rise of its evolutionary precursor, Mn-oxidizing

157 phototrophy[53] and before the Great Oxidation Event at 2.3-2.45 Ga[54,55]. Production of

158 atmospheric O_2 led to the formation of ozone, which shielded the immediate surface zone

159 from harmful UV rays. The success of cyanobacteria not only led to marked increases in

160 biomass production and deposition in shallow water environments (shelf, coastal marine, and

161 lacustrine) where high sedimentary rates prevail, but also to the colonization of arid and cold

162 surface environments by endolithic communities[56]. Our paleontologic record over the last

163 ~3000 Mya is dominated by carbonaceous sedimentary rocks from such environments[57].

164

165 On Mars, there may have never been an evolutionary drive to inhabit the surface. During the

166 Noachian, Mars was most likely cold, arid and oxidizing[58,59]. Fluvial channels and most crater

167 lakes on Noachian Mars once thought to have required some form of greenhouse atmosphere

168 in order to stabilize liquid water over geologic time scales, are now considered by some to

169 have formed within thousands of years[60,61], perhaps under a tenuous atmosphere in the

170 Noachian. The surface seemingly shifted from a cold but episodically wet landscape to a

171 frozen, hyperarid desert at the Noachian-Hesperian transition ca. 3600 Mya[62].

172

173 The success of surface life on Earth can be traced back to the evolution of oxygenic

174 photosynthesis in the Archean. The most recent molecular clocks have placed the origin of

175 photosynthesis at ~3000 Myr and the origin of oxygenic photosynthesis later than 2500 to

176 2600 Mya on Earth. Martian phototrophs would have had to attain these evolutionary

177 benchmarks by 3600 Mya, despite the generally frozen and arid surface conditions, fainter

178 sunlight, and the intense radiation flux from solar UV, Solar Energetic Particles (SEPs) and

179 Galactic Cosmic Rays (GCRs). By contrast, the evolution of methanogenesis, an important

180 metabolic pathway for subsurface life, occurred prior to the divergence of Euryarcheota and

181 Crenarcheota and represents one of the most ancient forms of metabolism[63].

182

183 Considering these challenges, it seems prudent to consider the possibility that photosynthesis

184 never evolved on Mars. Unless high-energy radiation could be harnessed as a form of energy,

185 as has been reported for certain fungal species[64], the radiated surface environment is an

186 impediment to the existence of surface life and an obstacle for the preservation of organic
187 materials[36]. With all this in mind, it seems time to reconsider the current Mars exploration
188 philosophy.
189
190 **A Mars exploration strategy focused on abiogenesis**
191 Much of the thinking about candidate landing sites for future landed missions has been aimed
192 at maximizing taphonomic potential by targeting sedimentary environments such as lacustrine
193 delta deposits. While this Mars exploration strategy is understandable, such an approach
194 suffers a major epistemological problem: Mars is not Earth. We must recognize that our entire
195 perspective on how life has evolved and how evidence of life is preserved is colored by the
196 fact that we live on a planet where photosynthesis evolved. Even if photosynthesis did evolve
197 on Mars, questions remain as to how successful surface life would have been, and whether
198 evidence of that life could have been captured in the sedimentary record.
199
200 Considering that some of the most ancient analogue habitats on Earth, hydrothermal and
201 subsurface environments, are mirrored on Mars, it is logical to search for the signs of
202 primitive life there in settings analogous to where it may have emerged here. We thereby not
203 only maximize our chances of finding chemotrophic life, but also of finding the evidence of
204 prebiotic chemistry that might have led to the formation of life in a sustained habitable
205 setting.
206
207 The search for biosignatures in hydrothermal deposits must also be questioned. For example,
208 silica sinter deposits of the type found in Gusev crater[32] are widely considered deposits with
209 high preservation potential for textural and chemical biomarkers on Earth. But, a significant
210 fraction of the biomass and biosignatures associated with silica sinters correspond to
211 photosynthetic bacteria that thrive in fluid mixing zones[65] and therefore the effects of a
212 possible absence of photosynthesis on biosignature preservation should also be considered in
213 this context.
214
215 Potential biosignatures in exhumed deep crustal rocks include the following: 1) isotopic
216 signatures of gasses (e.g. CH_4) trapped in fluid inclusions, 2) isotopic signatures of minerals,
217 fluids and organic matter trapped in veins and diagenetic replacements[66], 3) metal or
218 carbonate accumulations at redox gradients—especially indicating disequilibrium conditions,
219 4) biotextures in fractures and pores, 5) microfossils preserved in mineralized veins[66] or
220 diagenetic cements and concretions, and 6) important organic molecules such as nucleic
221 acids, lipids, and amino acids in fractures, fluid inclusions, and within mineral aggregates[67,68].
222 The detection of disequilibrium chemistry implicating life may perhaps be less satisfying than

223   the detection of fossilized microbial mats in lacustrine sediments, but such an approach might

224   actually teach us more about the origin of life. Because the chemical signatures from the

225   dawn of life have been entirely obliterated on Earth, finding these clues on Mars, a unique site

226   within the Solar System, would provide an invaluable window into our own history.

227

228   Given how little we understand about the origin of life on Earth, it makes sense to adopt a

229   broader plan to seek signs of life. In other words, it is perhaps more logical to seek evidence

230   of prebiotic chemistry that might have led to the formation of life in sustained habitable

231   settings rather than searching directly for evolved forms of surface life in ephemeral

232   environments. We could search for the signs of primitive life on Mars in settings analogous to

233   where it may have formed on Earth.

234

235   While concerns about the preservation potential of biosignatures in rocks from hydrothermal

236   and subsurface martian environments are important to consider, it is clear that preservation

237   potential does not present an ultimate stumbling block. The preservation of biomolecules

238   associated with hydrothermal activity in the extraterrestrial context has been validated by

239   their common occurrence in hydrous meteorites with signs of ancient hydrothermal

240   processing ($\leq 150°C$)[69]. Upon the cessation of the hydrothermal event, plunging temperatures

241   in martian environment would be ideal for preserving biosignatures (e.g. amino acid

242   enantiomeric ratio)[70]. Silica has been recognized for its significance in microfossil

243   preservation, and iron-silicate biomineralization in hot spring environments has been shown

244   to serve as a potent shield to UV radiation[71]. Biomarker preservation in subsurface

245   environments is a field that has hardly been explored, but biomarkers from Cretaceous

246   subsurface environments clearly demonstrate that preservation is possible[67].

247

248   By focusing our search on non-photosynthetic life, we not only maximize our chances of

249   finding biosignatures on Mars but also uncovering clues to abiogenesis, an aspect that should

250   be a key part of our exploration strategy. The quest to understand life's origins could be

251   described as "Follow the energy sources[46]: sulphur, iron and H_2." That mantra would lead us

252   to Mars, an iron and sulphur-rich planetary crust with abundant evidence for ancient

253   hydrothermal activity and H_2 production that could have fuelled an early chemosynthetic

254   biosphere.

255

256

257

258

259

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.

References

1.   Herd, C. D. K. *et al.* Origin and evolution of prebiotic organic matter as inferred from the Tagish Lake meteorite. *Science* **332,** 1304–1307 (2011).
2.   Morbidelli, A., Marchi, S., Bottke, W. F. & Kring, D. A. A sawtooth-like timeline for the first billion years of lunar bombardment. *Earth Planet. Sci. Lett.* **355–356,** 144–151 (2012).
3.   Sleep, N. H. & Zahnle, K. Refugia from asteroid impacts on early Mars and the early Earth. *J. Geophys. Res.* **103,** 28529–28544 (1998).
4.   Rosing, M. T. & Frei, R. U-rich Archaean sea-floor sediments from Greenland - indications of > 3700 Ma oxygenic photosynthesis. *Earth Planet. Sci. Lett.* **217,** 237–244 (2004).
5.   Dodd, M. S. *et al.* Evidence for early life in Earth's oldest hydrothermal vent precipitates. *Nature* **543,** 60–64 (2017).
6.   Mojzsis, S. J. *et al.* Evidence for life on Earth before 3,800 million years ago. *Nature* **384,** 55–59 (1996).
7.   Nutman, A. P., Bennett, V. C., Friend, C. R. L., Van Kranendonk, M. J. &

343   Chivas, A. R. Rapid emergence of life shown by discovery of 3,700-million-
344   year-old microbial structures. *Nature* **537,** 535–538 (2016).

345 8.   Bell, E. A., Boehnke, P., Harrison, T. M. & Mao, W. L. Potentially biogenic
346   carbon preserved in a 4.1 billion-year-old zircon. *Proc. Natl. Acad. Sci.* **112,**
347   14518–14521 (2015).

348 9.   Abramov, O. & Mojzsis, S. J. Thermal effects of impact bombardments on
349   Noachian Mars. *Earth Planet. Sci. Lett.* **442,** 108–120 (2016).

350 10. MILLER, S. L. & UREY, H. C. Organic compound synthesis on the primitive
351   earth. *Science* **130,** 245–51 (1959).

352 11. Szostak, J. W. *et al.* Synthesizing life. *Nature* **409,** 387–390 (2001).

353 12. Powner, M. W., Gerland, B. & Sutherland, J. D. Synthesis of activated
354   pyrimidine ribonucleotides in prebiotically plausible conditions. *Nature*
355   **459,** 239–242 (2009).

356 13. Oró, J. & Kimball, a. P. Synthesis of purines under possible primitive earth
357   conditions. I. Adenine from hydrogen cyanide. *Arch. Biochem. Biophys.* **94,**
358   217–227 (1961).

359 14. Ricardo, A., Carrigan, M. A., Olcott, A. N. & Benner, S. A. Borate Minerals
360   Stabilize Ribose. *Science (80-.).* **303,** 196 LP-196 (2004).

361 15. Hanczyc, M. M., Fujikawa, S. M. & Szostak, J. W. Experimental Models of
362   Primitive Cellular Compartments: Encapsulation, Growth, and Division.
363   *Science (80-.).* **302,** 618 LP-622 (2003).

364 16. Schmidt, B. E., Blankenship, D. D., Patterson, G. W. & Schenk, P. M. Active
365   formation of 'chaos terrain' over shallow subsurface water on Europa.
366   *Nature* **479,** 502–5 (2011).

367 17. Patthoff, D. A. & Kattenhorn, S. A. A fracture history on Enceladus provides
368   evidence for a global ocean. *Geophys. Res. Lett.* **38,** (2011).

369 18. Vance, S. *et al.* Hydrothermal systems in small ocean planets. *Astrobiology*
370   **7,** 987–1005 (2007).

371 19. Russell, M. J. *et al.* The drive to life on wet and icy worlds. *Astrobiology* **14,**
372   308–43 (2014).

373 20. Běhounková, M. *et al.* Timing of water plume eruptions on Enceladus
374   explained by interior viscosity structure. *Nat. Geosci.* **8,** 1–6 (2015).

375 21. Sparks, W. B. *et al.* Probing for Evidence of Plumes on Europa with
376   HST/STIS. *Astrophys. J.* **829,** 121 (2016).

377 22. Mulkidjanian, a. Y., Bychkov, a. Y., Dibrova, D. V., Galperin, M. Y. & Koonin,
378   E. V. PNAS Plus: Origin of first cells at terrestrial, anoxic geothermal fields.
379   *Proc. Natl. Acad. Sci.* **109,** E821–E830 (2012).

380 23. Deamer, D. W. & Georgiou, C. D. Hydrothermal Conditions and the Origin of
381   Cellular Life. *Astrobiology* **15,** 1091–1095 (2015).

382 24. Golombek, M. P. *et al.* Erosion rates at the Mars Exploration Rover landing
383   sites and long-term climate change on Mars. *J. Geophys. Res.* **111,** 1–14
384   (2006).

385 25. Zuber, M. T. The crust and mantle of Mars. *Nature* **412,** 220–7 (2001).

386 26. Lillis, R. J., Robbins, S., Manga, M., Halekas, J. S. & Frey, H. V. Time history of
387   the Martian dynamo from crater magnetic field analysis. *J. Geophys. Res. E*
388   *Planets* **118,** 1488–1511 (2013).

389 27. Kminek, G. & Bada, J. L. The effect of ionizing radiation on the preservation
390   of amino acids on Mars. *Earth Planet. Sci. Lett.* **245,** 1–5 (2006).

391 28. Lammer, H. *et al.* Outgassing history and escape of the martian atmosphere

392   and water inventory. *Space Sci. Rev.* **174,** 113–154 (2013).

393   29.   Carter, J., Poulet, F., Bibring, J. P., Mangold, N. & Murchie, S. Hydrous
394   minerals on Mars as seen by the CRISM and OMEGA imaging
395   spectrometers: Updated global view. *J. Geophys. Res. E Planets* **118,** 831–
396   858 (2013).

397   30.   Carter, J., Loizeau, D., Mangold, N., Poulet, F. & Bibring, J. P. Widespread
398   surface weathering on early Mars: A case for a warmer and wetter climate.
399   *Icarus* **248,** 373–382 (2014).

400   31.   Ehlmann, B. L. *et al.* Subsurface water and clay mineral formation during
401   the early history of Mars. *Nature* **479,** 53–60 (2011).

402   32.   Ruff, S. W. & Farmer, J. D. ARTICLE Silica deposits on Mars with features
403   resembling hot spring biosignatures at El Tatio in Chile. *Nat. Commun.* **7,**
404   1–10 (2016).

405   33.   Skok, J. R., Mustard, J. F., Ehlmann, B. L., Milliken, R. E. & Murchie, S. L. Silica
406   deposits in the Nili Patera caldera on the Syrtis Major volcanic complex on
407   Mars. *Nat. Geosci.* **3,** 838–841 (2010).

408   34.   Marzo, G. A. *et al.* Evidence for Hesperian impact-induced
409   hydrothermalism on Mars. *Icarus* **208,** 667–683 (2010).

410   35.   Turner, S. M. R., Bridges, J. C., Grebby, S. & Ehlmann, B. L. Hydrothermal
411   activity recorded in post Noachian-aged impact craters on Mars. *J. Geophys.*
412   *Res. Planets* **121,** 608–625 (2016).

413   36.   Cockell, C. S. *et al.* Habitability: A Review. *Astrobiology* **16,** 89–117 (2016).

414   37.   Whitman, W. B., Coleman, D. C. & Wiebe, W. J. Prokaryotes: The unseen
415   majority. *Proc. Natl. Acad. Sci. U. S. A.* **95,** 6578–6583 (1998).

416   38.   Onstott, T. C., Colwell, F. S., Kieft, T. L., Murdoch, L. & Phelps, T. J. New
417   Horizons for Deep Subsurface Microbiology. *Microbe* **4,** 499–505 (2009).

418   39.   Stevens, T. O. Subsurface lithoautotrophic microbial ecosystems (SLMEs)
419   in igneous rocks: Prospects for detection. *Instruments, Methods, Mission.*
420   *Investig. Extraterr. Microorg.* **3111,** 358–365530 (1997).

421   40.   Pedersen, K. Microbial life in deep granitic rock. in *FEMS Microbiology*
422   *Reviews* **20,** 399–414 (1997).

423   41.   Stevens, T. O. & Mckinley, J. P. Lithoautotrophic microbial ecosystems in
424   deep basalt aquifers. *Science (80-.).* **270,** 450–454 (1995).

425   42.   Coveney, R. M., Goebel, E. D., Zeller, E. J., Dreschhoff, G. A. M. & Angino, E. E.
426   Serpentinization and the origin of hydrogen gas in Kansas (USA).
427   *American Association of Petroleum Geologists Bulletin* **71,** 39–48 (1987).

428   43.   Lillis, R. J., Manga, M., Mitchell, D. L., Lin, R. P. & Acuna, M. H. Unusual
429   magnetic signature of the Hadriaca Patera volcano: Implications for early
430   Mars. *Geophys. Res. Lett.* **33,** (2006).

431   44.   Michalski, J. R. *et al.* Groundwater activity on Mars and implications for a
432   deep biosphere. *Nat. Geosci.* **6,** 133–138 (2013).

433   45.   Kelley, D. S. *et al.* A serpentinite-hosted ecosystem: THe Lost City
434   hydrothermal field. *Science (80-.).* **307,** 1428–1434 (2005).

435   46.   Parnell, J., Boyce, A. J. & Blamey, N. J. F. Follow the methane: the search for
436   a deep biosphere, and the case for sampling serpentinites, on Mars. *Int. J.*
437   *Astrobiol.* **9,** 193–200 (2010).

438   47.   Onstott, T. C. *et al.* Martian CH4: Sources, flux, and detection. *Astrobiology*
439   **6,** 377–395 (2006).

440   48.   Niles, P. B. *et al.* Geochemistry of Carbonates on Mars: Implications for

441   Climate History and Nature of Aqueous Environments. *Space Sci. Rev.* **174,**
442   301–328 (2013).

443   49. Russell, M. J., Hall, A. J. & Martin, W. Serpentinization as a source of energy
444   at the origin of life. *Geobiology* **8,** 355–371 (2010).

445   50. Dismukes, G. C. *et al.* The origin of atmospheric oxygen on Earth: the
446   innovation of oxygenic photosynthesis. *Proc. Natl. Acad. Sci. U. S. A.* **98,**
447   2170–5 (2001).

448   51. Soo, R. M., Hemp, J., Parks, D. H., Fischer, W. W. & Hugenholtz, P. On the
449   origins of oxygenic photosynthesis and aerobic respiration in
450   Cyanobacteria. *Science (80-.).* **355,** 1436–1440 (2017).

451   52. Shih, P. M., Hemp, J., Ward, L. M., Matzke, N. J. & Fischer, W. W. Crown
452   group Oxyphotobacteria postdate the rise of oxygen. *Geobiology* **15,** 19–29
453   (2017).

454   53. Johnson, J. E. *et al.* Manganese-oxidizing photosynthesis before the rise of
455   cyanobacteria. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 11238–11243 (2013).

456   54. Farquhar, J., Bao, H. & Thiemens, M. Atmospheric Influence of Earth's
457   Earliest Sulfur Cycle. *Science (80-.).* **289,** 756–758 (2000).

458   55. Lyons, T. W., Reinhard, C. T. & Planavsky, N. J. The rise of oxygen in Earth's
459   early ocean and atmosphere. *Nature* **506,** 307–15 (2014).

460   56. Davila, A. F. & Schulze-Makuch, D. The Last Possible Outposts for Life on
461   Mars. *Astrobiology* **16,** ast.2015.1380 (2016).

462   57. Veizer, J. & Mackenzie, F. T. in *Treatise on Geochemistry: Second Edition* **9,**
463   399–435 (2013).

464   58. Wordsworth, R. D., Kerber, L., Pierrehumbert, R. T., Forget, F. & Head, J. W.
465   Comparison of 'warm and wet' and 'cold and icy' scenarios for early Mars
466   in a 3-D climate model. *J. Geophys. Res. Planets* **120,** 1201–1219 (2015).

467   59. Wordsworth, R. *et al.* Global modelling of the early martian climate under a
468   denser CO_2 atmosphere: Water cycle and ice evolution. *Icarus* **222,** 1–19
469   (2013).

470   60. De Villiers, G., Kleinhans, M. G. & Postma, G. Experimental delta formation
471   in crater lakes and implications for interpretation of Martian deltas. *J.*
472   *Geophys. Res. E Planets* **118,** 651–670 (2013).

473   61. Fassett, C. I. & III, J. W. H. Fluvial sedimentary deposits on Mars: Ancient
474   deltas in a crater lake in the Nili Fossae region. *Geophys. Res. Lett.* **32,** 1–5
475   (2005).

476   62. Fassett, C. I. & Head, J. W. Sequence and timing of conditions on early Mars.
477   *Icarus* **211,** 1204–1214 (2011).

478   63. Vanwonterghem, I. *et al.* Methylotrophic methanogenesis discovered in the
479   archaeal phylum Verstraetearchaeota. *Nat. Microbiol.* **1,** 16170 (2016).

480   64. Dadachova, E. & Casadevall, A. Ionizing radiation: how fungi cope, adapt,
481   and exploit with the help of melanin. *Current Opinion in Microbiology* **11,**
482   525–531 (2008).

483   65. Kato, K. *et al.* Microbial Mat Boundaries between Chemolithotrophs and
484   Phototrophs in Geothermal Hot Spring Effluents. *Geomicrobiol. J.* **21,** 91–98
485   (2004).

486   66. Pedersen, K. *et al.* Evidence of ancient life at 207 m depth in a granitic
487   aquifer. *Geology* **25,** 827–830 (1997).

488   67. Klein, F. *et al.* Fluid mixing and the deep biosphere of a fossil Lost City-type
489   hydrothermal system at the Iberia Margin. *Proc. Natl. Acad. Sci. U. S. A.* **112,**

490   12036–41 (2015).

491   68.   Ringelberg, D. B., Sutton, S. & White, D. C. Biomass, bioactivity and
492   biodiversity: Microbial ecology of the deep subsurface: Analysis of ester-
493   linked phospholipid fatty acids. in *FEMS Microbiology Reviews* **20,** 371–377
494   (1997).

495   69.   Ehrenfreund, P., Glavin, D. P., Botta, O., Cooper, G. & Bada, J. L.
496   Extraterrestrial amino acids in Orgueil and Ivuna: tracing the parent body
497   of CI type carbonaceous chondrites. *Proc. Natl. Acad. Sci. U. S. A.* **98,** 2138–
498   2141 (2001).

499   70.   Bada, J. L. & McDonald, G. D. Amino Acid Racemization on Mars:
500   Implications for the Preservation of Biomolecules from an Extinct Martian
501   Biota. *Icarus* **114,** 139–143 (1995).

502   71.   Phoenix, V. R., Konhauser, K. O., Adams, D. G. & Bottrell, S. H. Role of
503   biomineralization as an ultraviolet shield: Implications for Archean life.
504   *Geology* **29,** 823–826 (2002).

505   72.   Poulet, F. *et al.* Martian surface mineralogy from Observatoire pour la
506   Mineralogie, l'Eau, les Glaces et l'Activite on board the Mars Express
507   spacecraft (OMEGA/MEx): Global mineral maps. *J. Geophys. Res.* **112,**
508   (2007).

509   73.   Murchie, S. *et al.* Compact reconnaissance Imaging Spectrometer for Mars
510   (CRISM) on Mars Reconnaissance Orbiter (MRO). *J. Geophys. Res.* **112,**
511   (2007).

512   74.   Michalski, J. R. & Niles, P. B. Deep crustal carbonate rocks exposed by
513   meteor impact on Mars. *Nat. Geosci.* **3,** 751–755 (2010).

514   75.   Wray, J. J. *et al.* Orbital evidence for more widespread carbonate-bearing
515   rocks on Mars. *J. Geophys. Res. E Planets* **121,** 652–677 (2016).

516   76.   Ehlmann, B. L., Mustard, J. F. & Murchie, S. L. Geologic setting of serpentine
517   deposits on Mars. *Geophys. Res. Lett.* **37,** (2010).

518   77.   Squyres, S. W. *et al.* Detection of Silica-Rich Deposits on Mars. *Science (80-.*
519   *).* **320,** 1063–1067 (2008).

520   78.   Michalski, J. R., Dobrea, E. Z. N., Niles, P. B. & Cuadros, J. Ancient
521   hydrothermal seafloor deposits in Eridania basin on Mars. **8,** 15978
522   (2017).

523

524

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 rocks   anoxygenic   oxygenic   GOE
oldest minerals   photosynthesis
?   oldest life   global oceans
?
?   intense impact
bombardments

MARS

Time before present (b.y.)

4   3   2   1   0

?   erosion
magnetic field   of atm
localized, ephemeral brine seeps on a frozen planet
seas & lakes   ?
hydrothermal
activity
?   intense impact
bombardments   global transition

window into early Earth

Legend	
○	FeMg smectitic clay
●	chlorite + prehnite
●	serpentine
●	crustal carbonate
●	crustal silica
★	fumarolic silica
☆	seafloor-type clays