**COEVOLUTION AS A GUIDING PRINCIPLE FOR BIOSIGNATURE EXPLORATION ON MARS (AND BEYOND).** N.A. Cabrol[1], J. Bishop[1], S.L. Cady[2], N. Hinman[3], J. Moersch[4], N. Noffke[5], C. Phillips[6], P. Sobron[1], D. Summers[1], K. Warren-Rhodes[1], and D.S. Wettergreen[7], [1]SETI Institute, 189N. Bernardo Avenue, Suite 200, Mountain View 94043. Affiliation for second author; [2]Pacific Northwest National Lab; [3]University of Montana; [4]University of Tennessee, Knoxville; [5]Old Dominion University, Norfolk, VA; [6] Jet Propulsion Lab; [7] Carnegie Mellon University, Robotics Institute, Pittsburgh. Corresponding author: (ncabrol@seti.org) and (Nathalie.A.Cabrol@nasa.gov).

**Overview:** With the search for biosignatures, the exploration of Mars is shifting from the characterization of habitability to that of a coevolution, *i.e.,* the spatiotemporal interactions of life with its environment. Yet, the intellectual framework underpinning the preparation of Mars 2020 and ExoMars along with future life-seeking missions is essentially the same as the one that has guided the exploration of Mars for the past 15 years [1-4]. This framework is articulated around the terrestrial analogy principle of habitability. While this principle is helpful in characterizing Mars habitability potential over time (and that of any planet), it is limiting – and potentially misleading – for the exploration of biosignatures as it focuses primarily on the spatiotemporal dynamics and general geographic distribution of environmental factors.

Coevolution synergistically considers both life and environment, and how they modify each other as cause or effect. As a result, it is a more effective, systemic, and dynamic approach than habitability alone for understanding how to detect, identify, and characterize (past/present) microbial habitats and biosignatures. As a result, new paths of investigations must be developed to advance our understanding of plausible coevolution models on early Mars, and to support biosignature exploration. They include: (1) revisiting intellectual frameworks, theories, hypotheses, and science questions from a coevolutionary perspective; (2) injecting an ecosystem view at all levels of biosignature exploration [5] *i.e.,* spatiotemporal scales, spectral resolution, orbit-to-ground detection and identification thresholds [*e.g.,* 6-7], landing site selection, and exploration strategies; and (3) designing and deploying new mission concepts to gain a high-resolution view of environmental variability at scales that are relevant to (past/present) martian microbial habitats.

**Coevolution as a Guiding Exploration Principle:** Biological processes on Mars, if any, would have taken place within the distinct context of an irreversible early collapse of the magnetosphere and atmosphere [*e.g.,* 8], greater climate variability and gradients, and specific geographic, planetary, and astronomical characteristics. These comprise the unique constraints of a coevolution that would have separated a martian biosphere from that of Earth very early. To evaluate their full effect on biosignatures, these constraints should be envisioned within an intellectual framework that includes life as (a) an interactive agent of transformation of its environment, and (b) a piece of a dynamic system of polyextreme environmental conditions with complex loops and feedback mechanisms.

**Examples of Reframed Core Hypotheses and Science Questions:**

***Hypothesis A*: *Prebiotic and biological processes as we know them developed on early Mars*.** *Example Questions*: (1) What role did environmental differences between Earth and Mars play in an early evolution of life on Mars? (2) What was the impact of unique physical features (*e.g.,* global dichotomy, high obliquity, lost magnetosphere and atmosphere, volcanic and tectonic characteristics) on the formation and spatiotemporal evolution of environmental pathways for biological dispersal, and biomass/biosignature repositories? (3) What does a comparison between the timing of early life evolution on Earth and the current environmental models for early Mars suggest about ancient habitable environments, habitat development potential, biological dispersal, biosignature preservation, detection thresholds; (4) What does the lack of obvious biosignatures at current resolution suggest about (a) the extent and duration of subaerial habitats, biomass accumulation and preservation potential, and (b) the detection and identification thresholds of integrated instrument payloads required from orbit to the ground.

***Hypothesis B: Mars developed a second, independent, and distinct genesis*.** *Example Questions:* (1) What distinct biological traits (*e.g.,* metabolism, structure, size, biogeochemical cycles) could have evolved from the unique terms of a martian coevolution (astronomical, planetary, environmental, geographic, climatic, other), and (2) what distinct traces of coevolution could they have left in the geological or spectral records? For instance, how can existing datasets be searched for unique geochemical, mineralogical, textural, and biochemical markers that could have stemmed from life's adaptation to the martian polyextreme environment?

***Hypothesis C*: *Life never developed on Mars – No coevolution*.** *Example Questions*: What are the critical exploratory steps to complete at the surface, subsurface, and deep underground, (and where), before such a conclusion can be reached?

**A Polyextreme and Complex Environment:** A martian coevolution would have been imprimted early by the development of a polyextreme environment [5, 9]. While the current approach to biosignature exploration considers multiple extreme factors, it often analyzes their impact individually, with limited attempts at a systemic approach, *i.e.,* the characterization of these interactions and their effects, [*e.g.,* 10-12]. Terrestrial analogs of such environments demonstrate that interactions between multiple extreme environmental factors (*e.g.,* UV radiation, thin atmosphere, aridity) generate complex loops and feedback mechanisms at various scales through combinations that may alternatively either magnify, decrease, and/or cancel their individual effects, and often override global (planetary) trends at the scale of the microbial-habitats scales [*e.g.,* 5, 9]. On Mars, these interplays would have been made even more complex and variable by changing obliquities:

*Understanding the spatiotemporal interplay of environmental factors, their relative dominance in time, the resulting interactions with biological processes, and the resulting biogeosignatures is key to conceptualizing a martian coevolution and finding biosignatures.*

*Understanding how this variability affected prebiotic and biological processes, as well as the development and footprint of microbial habitats, is critical for evaluating plausible biomass production, potential biosignature formation and preservation, and appropriate detection levels for instruments.*

At local (habitat) scale**,** the footprint and sustainability of microbial habitats in terrestrial analogs of extreme environments depend on the response of microorganisms to polyextremes, microclimates generated by synergies between microbial (metabolic) activity and local environmental factors, which trigger unique loops and feedback mechanisms. Changing environmental conditions would have thus affected martian habitats in a systemic way, with modifications and/or loss in connectivity networks, formation and isolation of microniches, and the production of very localized and specific sets of ecosystem conditions [5].

*Modeling plausible metabolic pathways and responses to variable polyextreme environmental factors is key for understanding adaption and survival potential of subaerial habitats over time, their spatiotemporal distribution, and biosignature formation and preservation potential.*

**Biological Architecture, Biosignatures, and Uncertainty Threshold:** Whether Mars developed life as we know or do not know it, crossing the uncertainty threshold (*i.e.* biosignature potential *vs.* confirmed biosignature) will require (a) development of knowledge on how coevolution could have shaped a martian biological architecture (*e.g.,* chemical structure, morphology, size, genetic makeup, metabolism) and its interactions with, and response to a polyextreme environment; (b) prioritization of observations, and (c) understanding of when a suite of observations constitutes an unambiguous and definitive confirmation of the presence of life.

The premise is that we should be capable of unambiguously ascertaining that a physical sample, and/or sets of data, will show evidence of biological activity and cannot be the result of abiotic processes. However, as long as this certainty cannot be achieved, a definitive conclusion cannot be reached, and evidence may remain at the level of biohints. Crossing the uncertainty threshold on the questions raised by astrobiology requires simultaneous advancement on multiple scientific fronts [13] to enable a holistic view on how a planetary environment may shape biological architecture, and conversely how biological processes influence the environment [e.g., 5,14].

Filling the current knowledge gaps (*e.g.,* origin and nature of life, biological architecture, biosignatures) demands the analysis of vast amounts of data from many scientific domains, and envisions countless probabilistic occurrences. This is an area where Artificial Intelligence (AI) and machine learning can provide a critical support for standard lab, field, and theoretical approaches and significantly speed up breakthrough discoveries [15].

**Conclusion:** These knowledge gaps identify promising key research areas, science questions, and technology challenges in the field of astrobiology. While they are presented here in the context of the exploration of Mars, coevolution, along with the questions, hypotheses, and approaches suggested here, could be regarded as primary guiding principles for the search for life in the Solar System and beyond.

**References: 1.** Mustard et al., 2012, (MEPAG), 155–205; **2.** Hayes et al., 2017, *Astrobiology* 17363–400; **3.** Williford et al., 2018, In: *From Habitability to Life* (in press); **4.** Vago et al., 2017, *ESA Bull.* 126:16–23; **5.** Cabrol, 2018, *Astrobiology* 18(1), doi: 1089/ast.2017.1756; ; **6.** Cabrol et al., 2017, *AbSciCon*, Mesa, Arizona. Abstract #3033; **7.** Phillips et al., 2017, *Astrobiol. Sci. Conf.*, #3373;**8.** Jakosky et al., 2017, *Science* 355:1408–1410; **9.** Cabrol et al., 2007, *Proc SPIE* 6694. doi:10.1117/12.731506; **10.** Jakosky and Phillips, 2001, *Nature* 412:237–244; **11.** Kreslavsky and Head, 2005, *Geophys Res Lett* 32, doi:10.1029/2005GL02264; **12.** Atri et al., 2013, *Astrobiology* 13:910–919; **13.** *NASA Astrobiology Strategy*, (2015), Hays, ed.; **14.** Knoll et al., 2005, *Earth Planet Sci Lett* 240:179–189; **15.** Cabrol et al., (2018) *49th LPSC*, #1275.

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