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Editorial: Mars analogs: Environment, habitability and biodiversity

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Editorial on the Research Topic
Mars analogs: Environment, habitability and biodiversity

Introduction

The Martian surface contains diverse lithologies (from sedimentary rocks to mafic-ultramafic igneous rocks) and ground patterns. These rocks record the late-stage evolution on the Martian surface from a temperate environment with bodies of liquid water to the current cold and hyper-arid environment. The constraints on the key parameters and processes for water-rock interaction, sedimentation of materials, and geomorphological development can provide important insights into environmental change and habitability. However, due to the difficulty in returning Martian samples to Earth and the limited remote-sensing data available from the Martian surface, many of the mysteries of Mars remain unresolved.

This Research Topic focuses on geological settings on Earth that are similar to the conditions on Mars. These Mars analogs are studied to infer possible processes operating on the Red Planet and their impact on habitability and the search for life. The Mars analogs on Earth span a variety of environments including the super-arid sedimentary plains (e.g., the Qaidam Basin in the north of the Tibetan Plateau, the Mojave Basin in the United States, and the Atacama Desert in South America; Azua-Bustos et al.; Peters et al., 2008; Sherwood Lollar et al., 2007; Xiao et al., 2017), the subsurface fracture waters in Precambrian cratons (e.g., the Canadian Shield, the Fennoscandian Shield, and the Kaapvaal Craton; Hays et al., 2017; Onstott, 2016; Preston and Dartnell, 2014), high salinity localities (e.g., Laguna de Tírez, salt mines, and deep-sea brines; Antunes et al., 2011; Antunes et al., 2020; Cockell et al., 2019; Fairén et al., 2023) as well as extremely cold and highly radiative environments (e.g., polar regions, thin atmosphere; DasSarma et al., 2020; Deming and Huston, 2000). These analog settings on Earth are more accessible and offer opportunities to collect high-quality mineralogical, geochemical, geochronological, and microbiological data through state-of-the-art technologies and instruments. Such data can provide a solid cornerstone for us to understand the cycles of water and other life-essential elements, the impacts of extreme conditions on habitability and biodiversity in extreme environments on Earth as well as on the limits of life, and the preservation and detection of biosignatures. Such research can also provide vital insights into the search for life on other planets and moons.

As previously highlighted by several authors (Wu et al., 2022), the study of such analog sites is essential for: 1) studying the limits of life (e.g., Azua-Bustos et al., 2012; DasSarma and DasSarma, 2017; Koschnitzki et al., 2021), 2) obtaining useful new microbial strains for astrobiological exposure experiments (e.g., Musilova et al., 2015; Beblo-Vranesevic et al., 2020), 3) analyzing long-term preservation and viability of biomolecules and cells (e.g., Gramain et al., 2011; Leuko et al., 2017; Schreder-Gomes et al., 2022), 4) developing and testing technology for life-detection in space missions (e.g., Harris et al., 2015; García-Descalzo et al., 2019; Lantz et al., 2020; Dypvik et al., 2021; Rull et al., 2022), and 5) defining and refining planetary protection measures (e.g., Rettberg et al., 2019).

The present Research Topic includes 10 papers, which include discussions on the origin of life and chirality, microbiology, biosignature, and geomorphology studies in multiple analog sites, as well as new insights into the effects of exposure to Martian-like conditions. The Research Topic call was well received, with a total of 65 contributing authors from 7 different countries around the world (Chile, China, Costa Rica, France, Spain, United Kingdom, and United States), reflecting global interest on this Research Topic. This is further attested to by the attention that it has garnered: at the time of writing, over 39,000 views of this Research Topic have been recorded.

Origin of life and chirality

One common starting point of discussions on Astrobiology centers on the origin of life and the transition from the pre-biotic world. Modelling and experimental data on the source, synthesis, and evolution of key biomolecules are a regular source of new developments providing important glimpses into how life might have been conditioned.

Earth has experienced a long period of habitable evolution toward the origin of life in its Hadean eon. Numerous experimental and theoretical approaches have suggested that the Earth was capable of prebiotic evolution toward complex molecules and life. However, the organic molecules that contributed to evolution may not have been formed by a geochemical process. Feng (2022) proposes that the ultralow temperature of the molecular cloud that was the precursor of our Solar System may have contributed to the synthesis of homochiral polymers with a slight variation in the chirality of the monomers. The result suggests that cosmic evolution prior to our Solar System may place some constraints on the biochemical nature of all life on Earth, with potential implications also for Mars.

In contrast, Guo et al. (2022) showcase that experimental geochemical reactions could lead to the selection of chirality of amino acids under plausible prebiotic conditions. The authors believe that geochemical energy-supported organic complexity may have played a role on the very early Earth. Wang et al. show experimentally that a strain of *Halomonas* from the Mariana Trench can grow on D-amino acids, the enantiomers that are typically not preferred by life, although the role of high hydrostatic pressure is uncertain. This is the first investigation on the existence of D-amino acids and associated microbial degradation activity that could possibly occur in subduction zones where tectonic activities result in the release of hydrothermal organic matter.

Biology of Mars analog sites

A significant portion of astrobiology studies focus on analyzing the (micro)biology of analog sites across the globe, as well as detecting evidence for the presence of life in such locations. These studies are essential for an increased understanding of the limits of life, biodiversity, resilience and adaptation of microorganisms being exposed to multiple extremes of relevance for Astrobiology, as well as long term viability of cells and their signatures under Martian-like settings.

The current Research Topic highlights the Atacama Desert, one of the most studied analog models for Mars, known for its age and combination of extreme aridity, high UV radiation, and highly saline soils. The extensive review by Azua-Bustos et al. provides an overarching perspective of over 20 years of astrobiological research in this magnificent location, with the focus being on the two most Martian-like ecosystems of the Atacama Desert: the coastal range, and the much drier hyperarid core. The authors reflect on some important insights and suggestions on what has been learned, namely, on the potential limits for life, where to look for evidence of life on Mars, as well as technical limitations arising from patchiness and limits on detectability.

In another contribution within this Research Topic Wang et al. looked at a very different setting, by exploring an acid-sulfate hydrothermal system in Costa Rica. This study analyzed the crater lake of the active Poás Volcano, Laguna Caliente and its microbial communities that can survive and thrive at extremely low pH (−0.87–1.5) and environmental fluctuations. Aerobic acidophiles, taxonomically assigned to *Acidiphilium* spp., dominated the fluid samples while functional analysis of metagenomic data obtained from lake fluid, bottom sediment and sulfur clump showed complete assimilatory sulfate reduction pathway and a near-complete SOX system for oxidizing thiosulfate to sulfate. The microbial communities were found to have the ability to use simple and complex sugars (e.g., polyhydroxybutyrate, PHB), and also to fix carbon via the Calvin-Benson-Bassham Cycle. Genes encoding for cytochrome c (Cyc2) and arsenite oxidase (Aox) were present, suggesting that some community members potentially gain energy via dissimilatory Fe(II) and As(III) oxidation. Genes that confer resistance to acid, heat and heavy metals were also detected. This work suggests that diverse metabolic potentials might be an adaptation strategy for life to exist in acid-sulfate hydrothermal systems on Mars. Furthermore, the perseverance of life in Laguna Caliente indicates that life on Mars could have thrived in analogous environments, stressing the need for the search for life in relict Martian acid-sulfate hydrothermal systems.

From an astrobiological perspective, the study of hydrothermal systems and their deposits also requires increased efforts to ensure the capability to interpret unambiguously modern biosignatures, their distribution patterns, and their association with physicochemical factors. Silicious hydrothermal sinters have long been recognized for their ability to preserve microbial biosignatures in exquisite detail. Since the *Spirit* rover's discovery of opaline silica in an ancient volcanic hydrothermal setting in Gusev crater, Mars, interest in the taphonomy of Earth analogues has grown rapidly. In this Research Topic, Megevand et al. investigated the molecular and isotopic profile of biomarkers along a thermal gradient in a hot spring from El Tatio, a geyser field in the Chilean Andes. This geyser field features abundant opaline silica deposits that resemble the nodular and digitate structures that were reported on Mars and that often host microbial fossils on Earth (Walter and Des Marais, 1993). The locally calibrated DNA-validated lipidic profile in the analyzed biofilms provided a modern (molecular and isotopic) end member to facilitate the recognition of past biosources and metabolisms from altered biomarkers records in ancient silica deposits at El Tatio analogous to Martian opaline silica structures. The study's approach uncovered the presence of *Roseiflexus*, *Chloroflexus*, and *Fischerella*, as well as several new cyanobacteria, while reporting the first detection of *Fischerella* biomarkers at temperatures of up to 72°C. This, together with the ecological peculiarities and proportion unclassified clades characterized, further highlights the ecological singularity of this site, and strengthens its astrobiological relevance.

Geomorphology of Mars analog sites

The study of Martian analogs has a strong component linked with geosciences, frequently associated with analyzing the formation and evolution of geological features on Earth and how they might provide insights into past and present conditions on Mars.

An example of relevant studies includes research on clay minerals, as their global distribution on the Martian surface demonstrates the liquid water activity on ancient Mars. Chlorite is the second-most common class of these minerals on the Martian surface, coexisting with illite in some regions. Previous studies have investigated the formation of this assemblage, but its post-depositional evolution has been mostly neglected, even though aqueous activities can alter the mineral assemblage and distribution. This Research Topic is addressed in the current Research Topic by a paper from Sun et al., analyzing post-depositional weathering of lacustrine-fluvial deposits collected from yardangs and dune-covering lake beds in the western Qaidam Basin, one of the largest and highest-altitude terrestrial Mars analogs. Mineralogical analysis revealed Fe-clinochlore and illite as the main clay components deposited as detrital particles, with electron microscopy of the deposits revealing that iron was released from clinochlore and formed ferrihydrite in fractures. The migration of Fe seems to be linked with and influenced by ephemeral waters as the major source of water in such a long-lasting hyper-arid climate, which might have parallels to the Nili Fossae region on Mars. Based on these results, the authors recommend that the reconstruction of the aqueous history of ancient Mars from surface minerals considers post-depositional processes, since groundwater/meteoric water may continuously interact with clay mineral-bearing deposits after their formation.

Sulfate salt deposits are also very relevant in astrobiological discussions of Mars. Hinman et al. looked at the poly-extremophilic and high-altitude Salar de Pajonales, a Ca-sulfate salt flat in the Chilean High Andes. Hinman et al. take a novel approach by studying the geomorphology of a ca-sulfate Salar in the Andes in the context of long-term changes in the Martian climate. In this high altitude salt flat, volume changes driven by hydration/dehydration, efflorescence/deliquescence, and recrystallization are brought about by physical and chemical processes related to changes in groundwater recharge and volcanism. Drawing parallels with Martian surface features previously thought to be related to freeze-thaw cycles, Hinman et al. offer an alternative interpretation of the features as the products of water-driven volume changes in salt deposits. Comparisons of Martian features with the changing morphology of features in the Salar offer an opportunity to infer Martian climatic changes. And the microenvironments studied provide unique insights into what might have been the last near-surface oases for microbial life on Mars before the climate transitioned to much drier conditions.

Effects of exposure to Martian conditions

Another very important research thread in this field is the analysis of how exposure to different Martian conditions might affect different type of organisms and biological processes. Results from such studies are at the core of understanding whether life on Mars might have been feasible across different periods and are frequently studied on specific types of microbes. These are also vital for discussions on planetary protection policies associated with missions to Mars and beyond.

This Research Topic includes a study focusing on microbes with a specific type of microbial metabolism. This paper, by Price et al., observed growth of three nitrate-dependent Fe^{2+} oxidizing (NDFO) bacterial strains (*Acidovorax* sp. BoFeN1, *Pseudogulbenkiania* sp. 2002 and *Paracoccus* sp. KS1) in a minimal medium with olivine as a solid Fe^{2+} source. Biomineralized cells were preserved the surface of olivine, which could be a potential biosignature for NDFO microorganisms in Martian samples. All three strains grew mixotrophically using nitrate as the electron acceptor in Martian simulant-derived Shergottite (SG) medium, and *Acidovorax* sp. BoFeN1 and *Pseudogulbenkiania* sp. 2002 in contemporary Mars (CM) medium. These findings suggested that if nitrate was readily available, NDFO microorganisms could thrive in basaltic environments (represented by SG medium) on Mars on the early surface of Mars and in the subsurface such as the Noachian epoch (4.1-3.7 Ga), and in aqueous environments (represented by CM medium). Notably, the growth of NDFO microorganisms in SG and CM media was not accompanied by significant Fe^{2+} oxidation.

In addition to microorganisms, studies on the effects of exposure to Martian conditions can be further expanded to more complex organisms, including humans. This is an increasingly relevant Research Topic, as future crewed missions to Mars are now under serious consideration. This will include a variety of challenges, given the drastic difference in environmental conditions and exposure to extended periods outside our planet so it is not surprising to observe an increase in the number of studies looking at the effects of exposure to extraterrestrial conditions. One clearly under-reported aspect is how such changes might affect circadian clocks. All animal life, including humans, has evolved different circadian clocks due to the multiple environmental circuits that Earth's system has uniquely developed. Astronauts either on the interplanetary journey to Mars or working on Mars for a relatively short period of time could face complications to their homeostasis. In a paper within this Research Topic, Luo et al. addressed this gap and discussed the effects of the Martian environment on human circadian rhythms. They suggested that the use of bright light may adjust human rhythms to the Martian day-night cycle and that plants with less robust rhythms may be more able to adapt to the day-night cycle on Mars. These could prove useful for supporting future plans for a longer term presence on the Red Planet.

Final remarks

As evidenced by the success and diversity showcased in this Research Topic, astrobiology is the subject of intense interest and activity by researchers across different areas of knowledge. The next few years of research centered on Earth, Mars, and beyond, are expected to deliver significant new developments on how and where to look for life outside our planet, and will hopefully bring us closer to answering the biggest question that humankind has ever asked: Are we alone in the Universe?

Author contributions

AA, MLV, DF, and YL wrote the first draft of the editorial article, and they also reviewed and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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