

# **The search for a signature of life on Mars: a biogeomorphological approach**

Dov Corenblit<sup>1\*</sup>, José Darrozes<sup>2</sup>, Frédéric Julien<sup>3</sup>, Thierry Otto<sup>3</sup>, Erwan Roussel<sup>1</sup>, Johannes Steiger<sup>1</sup>, Heather Viles<sup>4</sup>

<sup>1</sup>Université Clermont Auvergne, CNRS, GEOLAB – F-63000 Clermont-Ferrand, France.

<sup>2</sup>Université Paul Sabatier, CNRS/IRD, GET – F-31062 Toulouse, France.

<sup>3</sup>CNRS, ECOLAB, Université Paul Sabatier, CNRS, INPT, UPS, F-31062 Toulouse, France.

<sup>4</sup>School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom.

\*Corresponding author: Dov Corenblit, Université Clermont Auvergne, CNRS, GEOLAB, 4 rue Ledru, 63000 Clermont-Ferrand, France; Tel: +33 (0)4 73 34 68 04; Fax: +33 (0)4 73 34 68 24; *E-mail*: dov.corenblit@uca.fr

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## **Abstract**

Geological evidence shows that life on Earth evolved in line with major concomitant changes in Earth surface processes and landforms. Biogeomorphological characteristics, especially those involving microorganisms, are potentially important facets of biosignatures on Mars and are generating increasing interest in Astrobiology. Using Earth as an analog provides reasons to suspect that past or present life on Mars could have resulted in recognizable biogenic landforms. Here, we discuss the potential and limitations of a biogeomorphological approach in identifying the subsets of landforms modulated or created through biological processes, and

thus presenting signatures of life on Mars. Subsets especially involving microorganisms that are potentially important facets of biosignatures on Mars are proposed: (i) weathering figures, biocrusts, patinas and varnishes; (ii) microbialites and microbially induced sedimentary structures (MISS); (iii) bioaccumulations of skeletal remains; (iv) degassing landforms; (v) cryoconites; (vi) self-organized patterns; (vii) unclassified non-analog landforms. We propose a biogeomorphological frequency histogram approach to identify anomalies/modulations in landform properties. Such detection of anomalies/modulations will help to track a biotic origin and lead to the development of an integrative multi-proxy and multi-scale approach combining morphological, structural, textural and geochemical expertise. This perspective can help to guide the choice of investigation sites for future missions and the types and scales of observations to be made by orbiters and rovers.

**Key words:** life signatures on Mars – biogeomorphology – landform shape – landform structure – landform texture – microorganisms.

## 1. Introduction

The search for past or present extraterrestrial signatures of life on telluric planets, moons, and asteroids is primarily focused on the search for biologically influenced minerals, organic chemical biomarkers, Carbon and Sulfur isotopes on the ground surface and within the sub-surface (Röling *et al.*, 2016; Huang *et al.*, 2018) and in the atmosphere (Krasnopolsky *et al.*, 2004; Schwieterman *et al.*, 2018). The search for microfossils and living cells is also relevant (Marshall *et al.*, 2017).

However, as shown on Earth, the evolution of life caused major concomitant biogeomorphological changes in Earth surface processes and landforms, i.e. that life is seen to passively or actively contribute to landform creation and modulation (Viles, 1988; Butler, 1995). It is now recognized that the surface geomorphology of Earth contains numerous types of detectable past and present signatures of life, from microscopic to regional scales, other than solely fossilized microorganisms or biologically influenced minerals and organic chemical biomarkers (Corenblit *et al.*, 2011). Earth's landform history thus provides unique insights into the effects of biotic processes added to purely abiotic planetary surface processes and landforms. The consideration of Martian history, especially the Noachian period ( $< 3.6$  Ga ago), provides reasons to suspect that even under challenging arid, acidic and oxidizing conditions, life could have emerged, evolved and survived (Fernández-Remolar and Knoll, 2008; Westall *et al.*, 2013). Such life potentially could have affected surface landforms on Mars (Noffke, 2014).

Geomorphological characteristics (i.e. surface and sub-surface form, structure and texture) may be important facets of biosignatures that are generating increasing interest in Astrobiology (Gorbushina *et al.*, 2004; Naylor, 2005; Cady and Noffke, 2009; Noffke *et al.*, 2013; Westall *et al.*, 2015). Martian landform characteristics, at all scales from millimeters to thousands of square kilometers, are now visible and quantifiable in two and three dimensions

thanks to recent developments of rover, orbiter and space probe equipment. Scheduled to launch in 2020, the ExoMars rover (from ESA/Roscosmos) will be equipped with devices able to detect surface and sub-surface biogeomorphological signatures of life from micro- to landscape scales: the PanCam instrument with two wide-angle stereo cameras and one high-resolution camera for 2 and 3 dimensional high-resolution investigations of rock texture at a distance ranging from 1 to 100 m and with a spatial resolution of 1 cm for close objects; the WISDOM Ground Penetrating Radar able to establish stratigraphy down to 3 m in depth; the close-up imager CLUPI that will study rock targets at 0.5 m with sub-millimeter resolution; the contact instruments that will investigate outcrops, rocks, and substrate debris and their macroscopic texture, structure, and layering. These instruments, in particular, are designed for the search for morphological biosignatures on rocks and sediments (Coates *et al.*, 2017; Vago *et al.*, 2017). In such technological contexts, as stressed by Naylor (2005), Earth biogeomorphology and its deep understanding of eco-evolutionary feedbacks between geomorphological processes and organisms (for a review see Corenblit *et al.*, 2011) can contribute to identifying geomorphological life signatures on Mars.

## **2. Defining landform groups and their biotic subsets**

Geomorphological systems are controlled by local place- and/or time-contingent factors (Phillips, 2006). They are typically non-linear, exhibiting chaotic behavior with events occurring at small spatiotemporal scales producing at larger scales multiple potential response trajectories of geomorphological change (Perron and Fagherazzi, 2012). Furthermore, on Mars, the chemical nature and physical behavior of the available rocks, sediments and ice, as well as chemical composition of the atmosphere, pressure, gravity, and temperature which modulate the agents acting on rocks, sediments and ice (i.e. weathering, erosion, transportation and deposition), vary from those on Earth. On Mars, unique physicochemical conditions could also lead to the occurrence of unclassified non-analog landforms that do not

have terrestrial analogs (Fig. 1a). For example, seasonal erosion driven by CO<sub>2</sub> sublimation in Martian regions covered by the seasonal CO<sub>2</sub> cap can produce ‘araneiform’ terrains (referred to as terrains covered by ‘spiders’) without any terrestrial analogs (Hao, 2019).

The difference in physicochemical conditions between Earth and Mars combined with the deterministic-chaotic nature of landforms prevents the prediction of some landform characteristics, but in most cases general patterns of landforms remain predictable. Landforms on the Earth and on Mars are indeed governed by universal laws that are largely independent of time and place and they can most of the time be classified into known landform groups (Phillips, 2006; Dietrich and Perron, 2006).

## *2.1. Landform groups and their modulations*

Geomorphological surveys of the surface of Mars have revealed that most Martian landforms are very similar to the ones described and analyzed on the Earth (Fig. 1b). If we refer to images, for example, of pebbles, layered deposits, hillslopes, landslides, canyons, gullies, fluvial channels and networks, dunes, yardangs, polygonal surface features or craters on the surface of Mars (non-exhaustive list), we observe that the general shape/patterns of these landforms are most commonly very similar to those found on Earth (Dietrich and Perron, 2006). For example, Runyon *et al.* (2017) have shown that, apart from vegetated parabolic dunes, all dune types found on Earth are represented on Mars. It is thus possible to define a universal set of known (classified) landform groups (Fig. 1b<sub>1</sub>) delineated by basic physical and chemical laws and originating from the same or equivalent processes as their terrestrial analogs (Thomas *et al.*, 2005; Baker, 2008).

The discipline of geomorphology has provided a global classification of recognizable terrestrial landform groups with adapted methods of characterizations (Hargitai *et al.*, 2015; Guilbert *et al.*, 2016). Baker (2008) pointed out that the reasoning by analogy formalized in geomorphology in the 19<sup>th</sup> century by Gilbert (1886) represents the only way to interpret a

landform when lacking information on formative processes. Comparative planetary geomorphology uses reasoning by analogy with the basic assumption that the same or equivalent processes result in landforms displaying similar global characteristics. Gilbert's analogical method does not formally establish a causal association, but it promotes successful reasoning *via* abductive inference (Baker, 2008). As stressed by Hargitai *et al.* (2015), terrestrial geomorphological analogs are helpful in identifying morphogenetic processes of similar-looking extraterrestrial landforms of unknown origin and which cannot be monitored in detail.

Schumm (1991) noticed that a landform may be generally singular in form without being unique in form (in Baker, 2008). Modulations in landform characteristics occur in each landform group with specific combinations of physical intrinsic and extrinsic factors and the history and initial conditions of their interactions (Perron and Fagherazzi, 2012). Landform modulations indeed inevitably occur on Earth and on Mars according to the local context and all the more between Earth and Mars. For example, Martian sand dune morphology, texture, and behavior differ from those on Earth (Hayward *et al.*, 2007). However, unclassified non-analog dune modulations such as 'incipient barchan' and 'fortune cookie' dunes also occur on Mars (De Hon, 2006). The more components, variables or processes included in the representation of any landform group, the more singular the resulting landforms are.

## 2.2. *Biogenic landforms*

Biogeomorphology shows that life produces landforms with a distinctive shape, structural and textural signatures from those produced by purely abiotic landforms (Fig. 1b<sub>2</sub>) (Bertoldi *et al.*, 2011; Corenblit, 2018). Without life on Earth, certain landscapes would likely be more or less shaped differently, for example, hillslopes would be largely rocky and much more irregular (Dietrich and Perron, 2006) and meandering rivers would be rare (Davies and Gibling, 2011; McMahon and Davies, 2018). We define a 'biogenic landform' as any

landform that records a past or present detectable biotic influence (excluding that of humans) at any spatial scale. Earth classification of biogeomorphological processes (Jones *et al.*, 1994; Naylor *et al.*, 2002; Corenblit *et al.*, 2011; Fig. 2) which lead to detectable biogenic landforms using current knowledge and tools may have utility in the search for biosignatures on Mars. The physicochemical characteristics of the surface of Mars are well established, but many uncertainties related to the structure and functioning of a hypothetical life on Mars remain. The Earth analog combined with current knowledge about the origin and evolution on life (e.g. Fowler *et al.*, 2002; Luisi, 2006; Knoll, 2015) and its effect on geomorphology represents the only existing framework for defining biogenic criteria of landforms. This reasoning by analogy is also undertaken using the geochemical approach applied to the search on Mars of minerals, organic chemical markers and isotopes that are known to be biologically influenced on the Earth.

At the Earth's surface, numerous groups of biogenic landforms have been detected from regional to microscopic scales (Fig. 3). The high diversity of terrestrial biogenic landform groups related to the activity of many kinds of different micro- to macroscopic species offers the possibility to select those that could potentially occur on Mars. The search for potential Martian biogenic landform groups must be based in particular on the consideration of the geomorphological conditions in the Noachian (< 3.6 Ga ago) when surface liquid water probably occurred. It may also consider the most probable types of organisms that could have developed in surface water, and that potentially survived until the present in restricted habitats (Westall *et al.*, 2013). The recent discovery of a subsurface body of about 20 km of liquid water under the planet's south polar ice cap (Orosei *et al.*, 2018) increases the possibilities to find present microbial life.

### 3. Targeting the geomorphological effects of unicellular microorganisms on Mars

Determining biotic origins of landforms on Mars depends on our ability to identify candidate landform groups associated with candidate organism groups. Among the variety of biogenic processes (Fig. 2) that produce detectable biogeomorphological signatures from microscopic to regional scales on the Earth's surface (for a review see Corenblit *et al.*, 2011) (Fig. 3), the roles of unicellular microorganisms (archaea, bacteria and eukarya domains: e.g. protozoa, unicellular algae and unicellular fungi) are of particular importance (Cady, 2001; Landis, 2001; Cady and Noffke, 2009; Westall *et al.*, 2013, 2015). Microorganisms have been demonstrated to be tenacious, encompassing extremophile species with remarkable resistance to extremes of temperature, salt content, pH, pressure, radiation, or heavy metal concentrations (Pikuta *et al.*, 2007). Microorganisms grow intimately with rocks and sediments and derive nutrients, shelter and water from them. They are known to be capable of leaving many kinds of detectable influences on mineral precipitation and transformation, weathering, erosion and deposition features (Carter and Viles, 2004; Viles, 2008, 2012; Noffke, 2010).

On early Mars, under similar conditions as found on early Earth, microbial life could have colonized a primitive ocean, as well as more or less ephemeral and interconnected craters, playa lakes, volcanic aquifers, hot springs and hydrothermal seafloors (Westall *et al.*, 2013; Grotzinger *et al.*, 2014; Michalski *et al.*, 2017; Cabrol, 2018; Huang *et al.*, 2018) and even fluvial systems (Homann *et al.*, 2018). Vago *et al.* (2017) pointed out that in order to maximize the probability of finding life signatures on Mars, we need to target the early Noachian spots exhibiting the highest surface hydrological connectivity and select areas preserving evidence of prolonged water-rich environments suitable for the emergence of life (see also Westall *et al.*, 2013). The preservation of geomorphological signatures in rocks and sediment records promoted by early microorganisms on Mars in ancient submerged spots



remains a possibility (Noffke *et al.*, 2013; Westall *et al.*, 2015). In present conditions, the surviving of living microorganisms is not to be excluded either, such as extremophile microorganisms like those observed in Antarctic dry valley sandstones (Westall *et al.*, 2013; Mukan *et al.*, 2017) or in small transient playas of saturated brine (Landis, 2001).

Taking into account environmental conditions on Mars and current knowledge about the Martian geomorphology, it appears that influences of microorganisms in the search for a past or present biogeomorphological signature of life potentially include (Fig. 1b<sub>2</sub>): (i) weathering figures, biocrusts, patinas and varnishes (WBPV in Fig. 1); (ii) microbialites and microbially induced sedimentary structures (MISS); (iii) bioaccumulations of skeletal remains; (iv) degassing landforms; (v) cryoconites; (vi) self-organized patterns; (vii) unclassified non-analog landforms.

### *3.1. Weathering figures, biocrusts, patinas and varnishes*

At the Earth's surface, microorganisms are known to induce bioweathering, bioerosion or bioprotection. Cryptoendolithic microorganisms survive in Antarctic's cold desert within the narrow subsurface of rocks. They survive by growing in pores and their activity induces rock weathering producing visible signatures from microscopic to regional scales, for example, micron-scale silt formation, millimeter to centimeter-scale rock flakings, pittings, meter-scale mushroom rocks and karren features, kilometer-scale weathering landscapes (Friedmann, 1982; Viles, 2012). Bioprotection produces structures such as biocrusts, patinas and varnishes that can be observed in rock or sediment samples from the microscopic to the mesoscale (Naylor *et al.*, 2002; McLoughlin *et al.*, 2007; Viles, 2008, 2012). Viles (2012) reported recent studies indicating specific locations where mineralizing microbial mats occur on Earth which may provide analogs for past and present conditions on Mars, including around mud volcanoes, on intertidal flats and in permafrost fissures. Indeed, mound-like landforms interpreted as fossilized mud volcanoes have been identified within *Firsoff crater*, in the

*Arabia Terra* region on Mars (Pondrelli *et al.*, 2011). Mars intertidal shorelines also have been located suggesting the past existence of intertidal flats (Head *et al.*, 1999). Within fissures in permafrost environments, Pellerin *et al.* (2009) suggested that microbial communities in endostromatolites (i.e. fissure calcretes) in the Arctic are relevant analogs for the search for life near the edge of habitability.

Present cryptoendolithic microorganisms that promote weathering or bioprotection could preferentially occur on Mars in mid to low-latitude periglacial regions, especially within subsurface permafrost and rocky environments, for example, in *Utopia Planitia* (Lobitz *et al.*, 2001; Ulrich *et al.*, 2012; Sun, 2013; McEwen *et al.*, 2014; Martín-Torres, 2015).

### 3.2. *Microbialites and microbially induced sedimentary structures*

Microbialites (e.g. stromatolites and thrombolites) and microbially induced sedimentary structures (MISS) represent manifestations of microbial processes that remain fossilized in geological records for billion of years from micro to regional scales (Noffke, 2009, 2010).

As pointed by Ibarra and Corsetti (2016), microbialites are a target for astrobiological investigation on Mars. Carbonate is the main chemical sediment for enhancing morphological biosignatures on Earth but not on Mars. Allwood *et al.* (2013) suggested that relevant chemical sediment on Mars is likely to be a sulfate mineral such as gypsum. A variety of gypsum stromatolites exist on the Earth (Vogel *et al.*, 2009; Strohmenger *et al.*, 2010; Strohmenger and Jameson, 2017), for example, the one related to the Miocene gypsum successions in Cyprus, Crete, and in Sicily (Allwood *et al.*, 2013). Earth evaporitic gypsum deposits could represent an analog for environments on Mars where gypsum has been detected (Bibring *et al.*, 2005) and interpreted as possible evaporitic sediments (Grotzinger *et al.*, 2005). Landis (2001) suggested that on Mars, liquid water would have been highly concentrated brine solution and that any past or present Martian microorganisms would be similar to terrestrial extremophile halophiles such as for example, *Halobacterium halobium*

and *Halococcus salifodinae*. According to Allwood *et al.* (2013), the Martian evaporitic sulfate sequences should indeed be targeted for the search of life signatures because (i) Earth modern and ancient analogs showed the habitability of gypsum evaporites, (ii) they have a high potential of preservation of morphological biosignatures and also because (iii) these chemical sediments would have formed where liquid water once existed at the surface.

The different morphologies of MISS in siliciclastic and evaporitic settings are also considered to be promising candidates in the search for a past geomorphological signature of life in rock records on Mars, especially based on shape and texture of microscopic sediment (Wierzchos and Ascaso, 2002; Cady *et al.*, 2004; Noffke, 2010; Noffke *et al.*, 2008, 2013). They incorporate features from the millimetric to metric scales such as wrinkle structures, palimpsest ripples, roll-up and laminar structures. They originate from microbial mat formations including bacteria, archaea, protozoans, algae and fungi growing in the intertidal habitats of fluvial, marine and hypersaline environments (Thomas *et al.*, 2013).

Microbialites and MISS need to be searched for in priority areas likely to have been submerged or to have experienced benthic activity in the past. This is, for example, the case for the < 3.7 Ga *Gillespie Lake* Member on Mars that has been interpreted as an ancient playa lake environment and where centimetric to metric MISS-like structures have been previously observed in Curiosity rover mission images (Noffke, 2014).

### 3.3. Bioaccumulations of skeletal remain

Prokaryotic and eukaryotic microorganisms can lead to the formation of siliceous oceanic, lacustrine or hot spring deposits such as diatomites and cherts. Such structures are created by the deposition of diatom and radiolarian microscopic frustules. On Earth, they can be observed from meso to regional scales and they represent a candidate for the search for geomorphological signatures of life on Mars in areas known to have been submerged by water in the past, for example, oceanic basins and crater lakes. This hypothetical situation is, at

present, not back up by any strong evidence from Mars, but Qu *et al.* (2015) suggested that Opaline silica deposits observed on Mars in *Gusev crater* by the Spirit rover, could represent structures where organic biosignatures have been preserved (see also Ruff and Farmer, 2016).

#### 3.4. Methane degassing landforms

Archaea are known to be anaerobic methanogen producers. Most of the methane stored in sediments originate from microbial activity (Valentine, 2002). Formisano *et al.* (2004) pointed to the possibility of large scale methane cryospheric storage on Mars. This gas could have been produced in the past and remained trapped in the crust or in the polar caps. It was discovered recently that traces of methane in the Martian atmosphere rise and fall seasonally. Mumma *et al.* (2009) suggested that this degassing originates from the destabilization of clathrates by high summer temperatures in specific locations. The seasonal degassing of methane can thus be explained by abiotic processes alone, but as pointed out by Webster *et al.* (2018), it could also be related to seasonal variations in microbial activity. Thus, a biotic origin of this methane and also of its seasonal release is not to be excluded. As suggested by Oehler and Etiope (2017), the occurrence of methane on Mars is thus of special interest because of its potential association with microbial life.

Centimetric to kilometric circular depressions occur in permafrost regions of Earth in relation to abrupt releases of methane trapped as hydrates (Andreassen *et al.*, 2017). Clathrates on Earth are very extensive in cold terrestrial environments and are a potential analog for the search of clathrates in related surface landforms on Mars. Therefore, the search of shallow circular depressions on Mars presenting equivalent geomorphology as those produced by degassing depressions on the Earth in permafrost should be considered. The release of biotic methane can also contribute to the origin of mud volcanoes, generally ranging from centimeters to tens of meters in height, for example, the mud volcanoes of *Berca* in Romania (Baciu *et al.*, 2007). Mud volcanoes on Earth are the result of a fluid-rich

subsurface bringing up fine material from relatively deep zones. Oehler and Allen (2012) pointed out that surface degassing mounds are likely to contain organic-rich shales concentrating and preserving organic geochemical biomarkers in sediments of varying ages, and potentially very ancient organic-rich shales. Oehler and Etiope (2017) highlighted many types of mounds on Mars detectable with orbiters that could be associated with methane release. For example, mud volcanoes ranging from 20 to 500 m in diameter have been reported on Mars in *Acidalia Planitia* region in the northern plains (Oehler and Allen, 2010). Pondrelli *et al.* (2011) reported mud volcanoes within *Firsoff crater*, in the *Arabia Terra* region of Mars. Hundreds of mounds of 100-500 m in diameter were observed on the crater floor. Komatsu *et al.* (2016) also reported in *Chryse Planitia* the occurrence of small edifice features up to a few km in diameter that are probable mud volcanoes.

Thus, the geomorphology of shallow and deep circular depressions and mud volcanoes represents, in addition to the analysis of their physicochemical composition, an opportunity to explore past or present occurrence of life at the subsurface of the planet Mars.

### 3.5. *Cryoconites*

On Earth, cryoconite holes are discrete surface geomorphological structures in which very specific ecosystems can develop in polar environments (Säwström *et al.*, 2002). The holes vary in width and depth from widths most generally ranging between 0.5 to 1.50 m and depths ranging from 0.4 to 0.6 m. However, Fountain *et al.* (2004) reported cryoconite holes of 5 m deep and > 30 m in diameter. Cryoconite holes originate from the concentration of dust combined with the activity of the most extremophile consortia of archaea, algae, cyanobacteria, fungi, and heterotrophic bacteria (Zawierucha *et al.*, 2017) within depressions on the surface of snow, glaciers, or ice caps. The dark colored biophysical concentrations lead to the formation of cylindrical holes as the dust and humic substance produced by the microbes decrease the surface albedo, thus increasing heat absorption and accelerating ice melting.

Cryoconite settles and concentrates at the bottom of these holes creating suitable habitat conditions for cold-adapted microbes and algae in a harsh supraglacial environment (Hodson, 2008). Such organisms can occur in the coldest and driest rocky and icy environments on Earth that were identified as analogs for the Martian environment (Wentworth *et al.*, 2005; Zawierucha *et al.*, 2017).

As suggested by Zawierucha *et al.* (2017), current knowledge on Earth glacier biota such as the one living in cryoconites can be used as a relevant model in Astrobiology for looking for microorganism survival strategies in icy conditions on planets and moons. The small to large ‘Swiss cheese terrain’ in the Martian ice (Thomas, 2000) could be a candidate for such Martian cryoconites.

### 3.6. *Self-organized regular geomorphological patterns*

Increasing literature illustrates the propensity of different biogeomorphological systems to generate regular, self-organized geomorphological patterns at the micro to regional spatiotemporal scales (Noffke *et al.*, 2013; Watts *et al.*, 2014). Regular, self-organized biogeomorphological patterns are caused by organism populations establishing where initial habitat conditions are improved or local resource availability is higher. Once a population establishes, positive feedback can occur locally (i.e. in their stand) whereby population growth of organisms leads to improved habitat conditions and protection against stress and disturbances, while resources decrease and/or stress increases at their vicinity (Rietkerk and Van de Koppel, 2008). Scale-dependent feedbacks generally occur in areas with high environmental constraints (e.g. deserts and polar zones) where engineer organisms regulate their growth or reproduction in response to physical processes and severe habitat conditions, or when physical processes and habitat conditions are, at least to some extent, regulated by the activity of engineer organisms. Such dynamics lead to specific geomorphological signatures, for example, regular distribution of depressions, mounds or strips which occur on surfaces

colonized by plants or animals but also occur on microbially-affected surfaces such as photokarren (Lundberg *et al.*, 2010). Bowker *et al.* (2014) showed that biocrust landscapes on the Colorado Plateau display self-organized geomorphological patterns visible from micro to mesoscales with distinctive parallel ridge and ‘valley’ morphology (for further examples, see Weber *et al.*, 2016). Thomas *et al.* (2013) showed that Kinneyia, a class of MISS forming in intertidal habitats covered by microbial mats, are characterized by regular self-organized ripples. The regular structure originates from a Kelvin–Helmholtz-type instability induced in the microbial viscoelastic film under flowing water. Riding and Tomas (2006) have suggested such self-organizational dynamics also occur on stromatolite reef crusts where peloids and inter-peloid space originate concurrently through bacterial degradation of organic matter, which leads to a regular spacing between the peloids.

### 3.7. *Unclassified non-analog landforms*

Unclassified non-analog surface landforms on Mars should also be considered as potentially originating from a biological activity. An unexpected category of life form on Mars combined with the geomorphological non-uniformitarian principle could indeed generate unknown biogeomorphological patterns and dynamics.

## **4. Disentangling abiotic and biotic components of landforms**

Much care must be taken in the search for a geomorphological signature of life as each of the biogenic landforms and patterns mentioned above are not unequivocal. They can be microbially-induced, but they can also be produced by strictly abiotic processes (Hallet, 1990; McLoughlin *et al.*, 2008; Davies *et al.*, 2016, 2018; Noffke, 2016; Knoll and Nowak, 2017). Noffke (2010) discussed a possible abiotic texture or structure for each possible biotic texture or structure of MISS, from the environmental context to the microscale. The author pointed to the importance of this differentiation step in the search for life signature. There is indeed clear

potential for the misidentification of biosignatures on Earth and, all the more, on Mars (Cady *et al.*, 2004; Noffke, 2014; Davies *et al.*, 2016). For example, stromatolites in their simplest form may be indecipherable from abiotic structures (Clarke and Stoker, 2013; Knoll and Nowak, 2017). As stressed by Davies *et al.* (2016) and McMahon *et al.* (2018), in contemporary active sedimentary environments, the role of microorganic mats in the formation of sedimentary surface forms, structures and textures can be well established. However, as previously suggested by Noffke (2000), in the geological record, supporting contextual evidence for the biotic formation of sedimentary surfaces can be lacking, especially where there is a convergence of form between microbial and abiotic structures. But Noffke pointed out that the comparison of modern with ancient material makes it possible to identify fossil MISS.

#### *4.1. Unraveling biotic and abiotic components of landforms*

Although the role of microorganisms on geomorphology is well recognized (Naylor *et al.*, 2002; Viles, 2008, 2012) and offers a real perspective for the search of life on Mars, further research is needed to better understand and quantify under which conditions and scales microorganisms and geomorphological processes and landforms are most closely linked and detectable. On Mars, where life may have exhibited different behaviors to life on Earth, this may be even more problematic. Thus, criteria of biogenicity such as those proposed by Noffke (2010) must be further developed and tested experimentally in various situations in the search for geomorphological signatures of microorganisms in rocky and sedimentary structures. In the context of the important development of high accuracy Mars Rover imagery, the search for such a validation of visually diagnostic criteria of terrestrial biogenic landforms remains a priority (Cady *et al.*, 2004; Davies *et al.*, 2016).



It was also pointed out that for many landscapes the difference between abiotic and biogenic landforms lies in the frequency distributions of landform properties (e.g. mountain and dune steepness or curvature, river channel sinuosity and width, fractal dimensions of branching river networks, persistence and resistance of alluvial bars in rivers and tidal marshes, weathering and erosion rates on hillslopes) rather than in the presence or absence of particular landform types (Dietrich and Perron, 2006). The spatiotemporal modulations of landforms by organisms on the Earth's surface are still greatly underestimated, but recent findings suggest that, from micro to regional scales, such biogenic modulations are very common and should be studied using a set of key landform topographic, structural and textural properties likely connected with organism activities: for example, vegetated fluvial islands, salt marshes, mangroves, foredunes and mountainous hillslopes (Stallins, 2005; Gurnell and Petts, 2006; Bertoldi *et al.*, 2011; Davies and Gibling, 2011; Corenblit *et al.*, 2015; Eichel *et al.*, 2016), aquatic and terrestrial bioconstructions such as stromatolites, insect mounds and beaver dams (Naiman, 1988; Dangerfield *et al.*, 1998; Grotzinger and Knoll, 1999); bioturbated soils (Gabet *et al.*, 2003; Hasiotis *et al.*, 2004; Meysman *et al.*, 2006); weathered and eroded minerals, rocks and landscapes (Boyle and Voigt, 1973; Naylor *et al.*, 2002; Viles, 2008, 2012; Coombes *et al.*, 2017) (Fig. 2, 3). In the case of Mars, landform modulations could be used in the candidate landform groups, i.e. those possessing potentially a biotic origin, for identifying a signature of life.

We stress that finding solutions to unravel biotic and abiotic components of extraterrestrial landforms should become an additional challenge in Astrobiology. Determining a biotic origin of a landform on Mars will thus certainly depend on our ability to identify the geomorphological parameters and spatial scales that are affected in candidate landform groups in a singular way by microorganic activity. Very detailed empirical and experimental analyses of how microorganisms affect these parameters under varying physicochemical situations

should be a key for searching potential geomorphological signatures of life on Mars. As suggested by Cady *et al.* (2004), the constitution of a database of high resolution 2 and 3-dimensional textural images that distinguishes the suite of biotic-mediated morphological biosignatures from their abiotic analogs may help to avoid detection of false-positives for life signatures. Detailed quantifications of landform modulations in candidate groups would become useful indicators for the search for potential geomorphological signatures of life on Mars.

Based on the empirical and experimental knowledge of Earth analogs, classifications such as the one proposed by McLoughlin *et al.* (2007) for defining the biogenicity of endolithic microborings, which categorise the degree of certainty attributed to a given interpretation of a frequency histogram, must be used in combination with geological, morphological and geochemical expertise to detect biotic signatures. Davies *et al.* (2016) proposed the following classification that could be applied on Mars: (A) known to be abiotic in origin; (B) known to be microbial in origin, (ab) where there is uncertainty, and (Ab) or (Ba) where there is uncertainty but one interpretation is favored.

#### 4.2. A biogeomorphological frequency histogram approach

As previously suggested for landforms on Earth (Dietrich and Perron, 2006; Corenblit *et al.*, 2011), we recommend the use of frequency distributions of selected quantifiable Martian landform characteristics collected in candidate landform groups by rovers from micro- to mesoscales and related to the activity of microorganisms, for example: (i) surface textural properties such as complexity, entropy, tortuosity, porosity, roughness and fractal dimension; (ii) size, kinds and textural aspects of stratifications; (iii) occurrence, size and geometry of characteristic weathering features such as pits; (iv) mesoscale geometrical and slope-area characteristics of landforms.

Frequency analyses can be used to identify convergences with terrestrial biogenic signatures. For example, by comparing the distribution of terrestrial dune and Martian dune field areas, Hayward *et al.*, (2007) showed that Martian dune fields are much smaller in areal extent, probably because of differences between Earth and Mars in sand supply rates and wind energy. Divergences among strictly Martian landform groups could also support the identification of a possible geomorphological signature of microbial activity. We stress that the variability expressed within a histogram frequency of a given Martian landform group may be more or less strong according to the sensitivity of the geomorphological, and potentially the biological, properties to the local variations into the physicochemical environment. The analysis of both convergences with terrestrial analogs and divergences among strictly Martian landform groups is most relevant for weathering figures, biocrusts, patinas and varnishes, MISS, and self-organized landforms (FH in Fig. 1). In such an approach, histograms with bimodal (Fig. 4a) or skewed (Fig. 4b) shapes would potentially indicate a biotic influence on landforms (e.g. Song *et al.*, 2010). Based on the empirical and experimental developments, the classification proposed by Davies *et al.* (2016) could be applied in a quantitative manner in combination with frequency analyses (Fig. 4c,d). At this stage, the geochemical (GC in Fig. 1) approach should be used in a complementary way for validating or invalidating a biotic origin of the considered landform.

## 5. Concluding remarks

The main limitation for identifying signatures of life on Mars is probably no longer technology, but is rather our ability to identify candidate landforms and to make a clear, non-ambiguous, distinction between strictly abiotic and biotic components of candidate landforms. In this article, seven groups of Martian candidate landforms have been identified: (i) weathering figures, biocrusts, patinas and varnishes; (ii) microbialites and microbially induced sedimentary structures; (iii) bioaccumulations of skeletal remains; (iv) degassing

landforms; (v) cryoconites; (vi) self-organized patterns; (vii) unclassified non-analog landforms. However, further groups of candidate landforms may potentially be identified according to new developments and progress in microbial biogeomorphology.

In the search for the identification of biogenic landforms on Mars, the biogeomorphological frequency histogram approach should help identify the anomalies/modulations in landform properties that will help to confirm a biotic origin and lead to the development of an integrative multi-proxy approach combining morphological, structural, textural and geochemical expertise. The constitution of databases such as the *Mars Global Digital Dune Database* (MGD; Hayward *et al.*, 2007) established using orbital images provide the possibility to quantify geomorphological characteristics of targeted landform groups. These landform characteristics could then be used for landform classifications and histogram frequency analyses. Certain potential biogeomorphological features, very close to those observed on Earth, could easily be identified with simple statistical tools such as those presented above. However, in the case of ancient and/or ‘diluted’ footprints of life by physical agents of erosion and weathering, the use of more powerful tools may become necessary, such as *wavelets* (Gaillot *et al.*, 1999) associated with *Singular Spectrum Analysis* (Golyandina and Osipov, 2007) or artificial intelligence tools/algorithms based on *deep learning* (Lombardi *et al.*, 2017). The biogeomorphological approach together with its related techniques should be tested on Mars before further development for other telluric planets and their moons can be potentially envisaged.

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## Figure captions

**Fig. 1:** Different possible categories of Martian landforms: **(a)** unclassified non-analog landforms; **(b)** classified (known landforms); **(b<sub>1</sub>)** abiotic (strictly physically driven landforms); **(b<sub>2</sub>)** six potentially biogenic landform groups on Mars: (i) weathering figures, biocrusts, patinas and varnishes (WBPV); (ii) microbialites and microbially induced sedimentary structures (MISS); (iii) bioaccumulations of skeletal remains; (iv) degassing landforms; (v) cryoconites; (vi) self-organized patterns. FH: frequency histogram analysis; BC: biochemical analysis.

**Fig. 2:** Main existing biogeomorphological processes (numbered from 1 to 6) shaping biogenic landforms. The model was built from the combination of classifications by Jones *et al.* (1994), Naylor *et al.* (2002) and Corenblit *et al.* (2011). Biogenic landforms likely to occur on Mars are indicated in red. The acronyms of 25 main biogenic landform groups on Earth are: **AIT**: animal and insect trails (e.g. surface and below ground traces); **AMB**: animal macroendolithic borings (holes); **BC**: biocrusts; **BEP**: beaver dams and ponds; **CD**: coppice dunes; **CFD**: coastal foredunes; **CH**: cryoconite holes; **FF**: fluvial floodplain; **H**: hummocks; **LIM**: large insect mounds (e.g. termite and ant mounds). **MDL**: methane degassing landforms (i.e. craters and mud volcanoes). **MEB**: microbial endolithic borings; **MISS**: microbial induced sedimentary structures; **MP**: microbial phytokarst; **MPBA**: massive passive biotic accumulation (skeleton deposits); **MRW**: microbial rock weathering features; **MS**: microbial speleothems; **MSF**: mangrove and saltmarsh flats; **PFI**: pioneer fluvial islands; **PSR**: polychaete sandy reefs; **RCR**: rudist and coral reefs; **SAIC**: small animal and insect constructions (e.g. nests, mounds, galleries, wallows); **SL**: smoothed and rounded landscape; **SR**: stromatolite reefs; **SRH**: smoothed and rounded hillslopes.

**Fig. 3:** Model of spatiotemporal occurrence of the main biogenic landform groups (see meaning of acronyms in the caption of Fig. 2) on Earth based on a literature review. The numbers indicate the related processes as presented in Fig. 1. Biogenic landforms likely to occur on Mars are indicated in red.

**Fig. 4:** Two hypothetical frequency histograms of geomorphological properties related to abiotic and biotic signatures: **(a)** bimodal shape; **(b)** skewed shape. The grey histograms correspond to the sum of biotic (green) and abiotic (orange) histograms. A quantitative adaptation of Davies *et al.* (2016) classification categorizing the degree of certainty attributed to a given interpretation of the frequency histograms is given in **(c)** and **(d)**: **(A)** Landform modulations are known to be abiotic in origin; **(B)** they are known to be biotic in origin, **(ab)** there is uncertainty, and **(Ab)** or **(Ba)** there is uncertainty but one interpretation is favored. In this idealistic representation, the abiotic and biotic frequency distributions largely differ, but many different configurations from full overlap to full separation can be expected. Frequency distributions can be produced with several quantitative key shape, structural and textural variables. Inspired by Dietrich and Perron (2006).

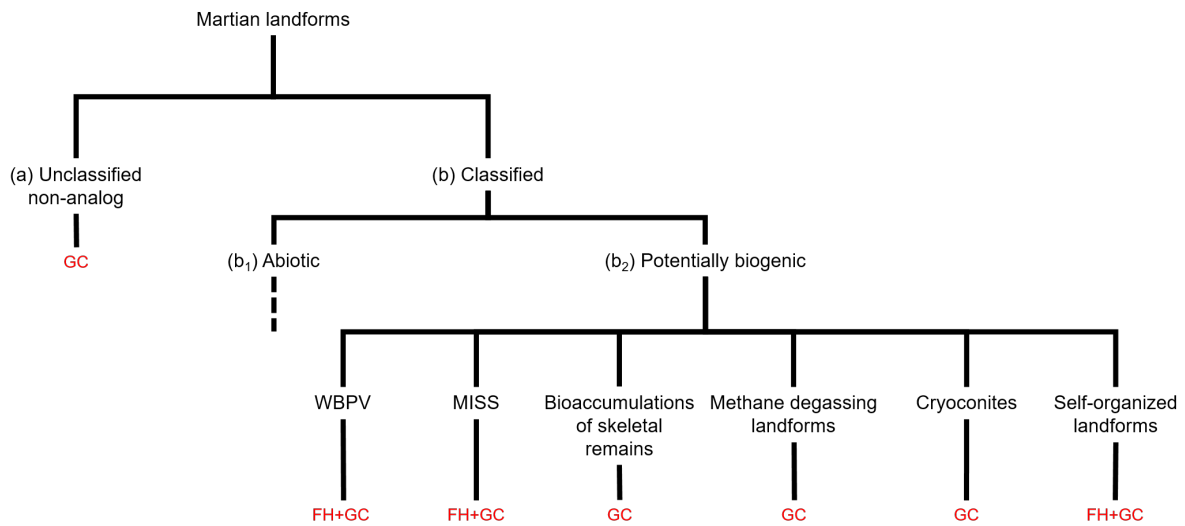


Figure 1

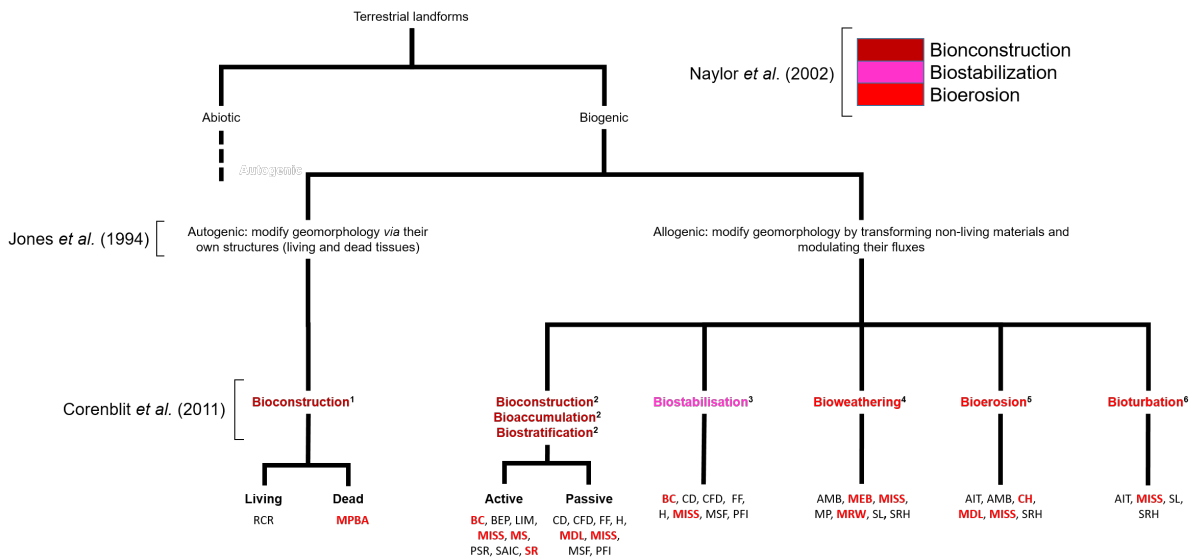


Figure 2

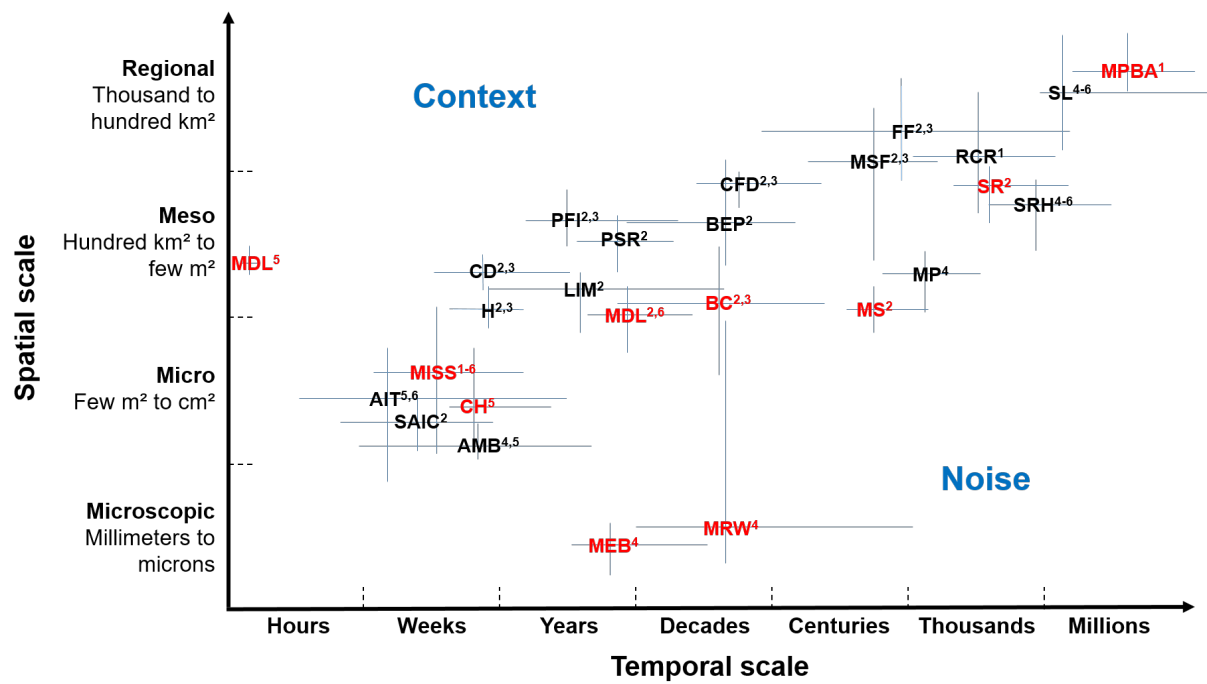


Figure 3

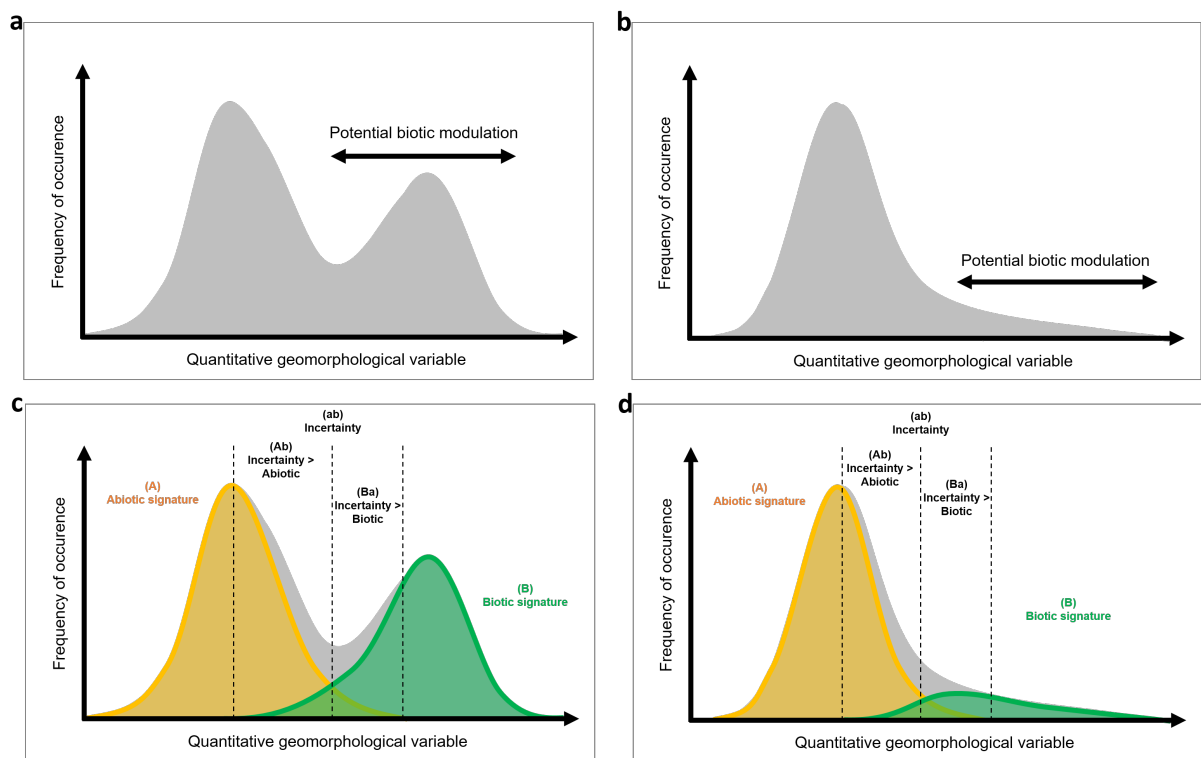


Figure 4