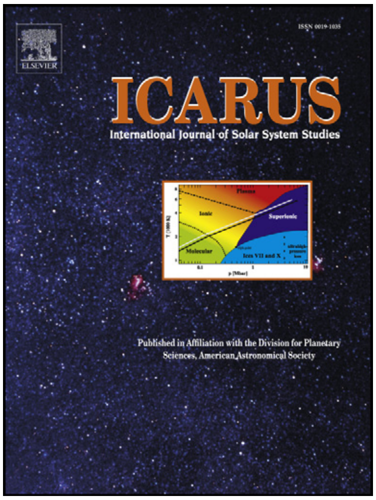

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Charles S. Cockell, Matt Balme, John C. Bridges, Alfonso Davila, Susanne P.
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Uninhabited Habitats on Mars

Charles S. Cockell
School of Physics and Astronomy, University of Edinburgh, James Clark Maxwell Building,
Mayfield Road, Edinburgh, EH9 3JZ, UK
Email: c.s.cockell@ed.ac.uk, Tel: +44 1908 652588

Matt Balme
CEPSAR, Open University, Milton Keynes, MK7 6AA, UK

John C. Bridges
Space Research Centre, Department of Physics & Astronomy, Michael Atiyah Building,
University of Leicester, University Road, Leicester, LE1 7RH, UK

Alfonso Davila
SETI Institute, 515 N. Whisman Road Mountain View, CA 94043, USA

Susanne P. Schwenzer
CEPSAR, Open University, Milton Keynes, MK7 6AA, UK

Investigations of Mars as a potential location for life often make the assumption that where there are habitats, they will contain organisms. However, the observation of the ubiquitous distribution of life in habitable environments on the Earth does not imply the presence of life in Martian habitats. Although uninhabited habitats are extremely rare on the Earth, a lack of a productive photosynthetic biosphere on Mars to generate organic carbon and oxygen, thus providing a rapidly available redox couple for energy acquisition for life and/or a lack of connectivity between potential habitats potentially increases the scope and abundance of uninhabited habitats for much of the geological history of the planet. Uninhabited habitats could have existed on Mars from the Noachian to the present-day in impact hydrothermal systems, megaflood systems, lacustrine environments, transient melted permafrost, gullies and local regions of volcanic activity; and there may be evidence for them in Martian meteorites. Uninhabited habitats would provide control habitats to investigate the role of biology in planetary-scale geochemical processes on the Earth and they would provide new constraints on the habitability of Mars. Future robotic craft and samples returned from Mars will be able to directly determine if uninhabited habitats exist or existed on Mars.

Keywords: uninhabited habitats, Mars, life, craters, volcanoes

1. Introduction

All environments in the Universe can be placed into one of three categories, which can be represented as a habitability 'triad' (Figure 1). An environment can be uninhabitable, either because of a physical (e.g. extreme temperature) or chemical (e.g. high concentrations of heavy metals) limitation, or the lack of a vital element required for life (e.g. nitrogen). Uninhabitable environments are often easy to identify and include obvious candidates such as the core of the Earth, the interior of the Sun and other similarly extreme locations. An environment can be habitable and inhabited. Many inhabited habitats can be located and observed on the surface and in the subsurface of the present-day Earth. Evidence for past inhabited habitats can be found in the rock record. The exact physical and chemical extremes that separate habitable from uninhabitable conditions are often undefined and subject to revision based on new discoveries in biology.

A third type of environment is one that is habitable, but uninhabited (Figure 1). Some clarification on nomenclature is required to describe these places. They are distinct from vacant 'niches' (Lawton, 1982; Chase and Leibold, 2003; Rohde, 2005; Lekevičius, 2009). A niche is a functional definition of a specific set of energy and nutrient availabilities that could be used by life. In a vacant niche they are unused. If a habitat has no life in it, it contains, by definition, vacant niche(s).

An uninhabited habitat could be described as a 'vacant habitat'. Previously in the literature this term has been used to mean a habitat vacant of one particular species, but inhabited by other types of life (Thomas et al., 1992; Osborne et al., 2001). The habitats discussed in this paper and previously (Cockell, 2011) are vacant habitats, but they are a specific type of vacant habitat – a habitat devoid of any life at all.

The term 'uninhabited habitat' more convincingly conveys a habitat that is not inhabited (i.e. being actively used as a habitat) by any life. There are instances in the literature in which it has been used synonymously with ‘vacant habitat’ to mean a habitat uninhabited by a specific species (Ohba et al., 1990; Bosakowski and Smith, 1997), but we would like to propose here that it is adopted to mean a habitat without any life.

The term, ‘lifeless habitat’, has been used to describe habitats in environments such as newly created lava flows (e.g. Gudmundsson, 1970). However, this term is problematic because uninhabited habitats on an inhabited planet could contain inactive life for which conditions are inappropriate for growth, for example the spores of an organism entrained from an inhabited region. Thus, an uninhabited habitat need not be lifeless. Similar problems are encountered with the term ‘sterile habitat’.

The assessment of the extent of uninhabited habitats is conservative and bounded by what we know about life. Environments classified as uninhabitable, for instance, might be suitable for life with biochemistries that are yet to evolve; therefore these environments only appear uninhabitable. Thus, the set of uninhabited habitats that are catalogued is a minimum set. A potential example of a habitat that was empty of life on account of biochemical limitations might have been areas of the Earth’s early land masses before microorganisms developed an ability to tolerate the extremes to be found there, such as desiccation (Battistuzzi and Hedges, 2009). However, in some cases, environments can be confidently said to be uninhabitable, regardless of potential biochemical adaptations. An example would be the centre of the Earth.

Any of the three types of planetary environment – uninhabitable, habitable and inhabited, and habitable but uninhabited – can be transient and they are can be interchangeable if environmental conditions alter in a particular location (certain uninhabitable environments such as the hot interior of some planets remain uninhabitable for the lifetime of a planet). For example, uninhabited habitats can become uninhabitable through deterioration in conditions that drive the habitat outside of habitable conditions. Uninhabited habitats can become inhabited by the influx of microorganismsm through the atmosphere or in water, capable of growing in the habitat (Figure 1).

Discussions on uninhabited habitats are absent from the ecological or planetary science literature probably because these environments are rare on the Earth, and where they do occur, they are usually transitory (Cockell, 2011). Two factors account for this. Firstly, in almost all habitats on the Earth that are connected to the photosynthetic biosphere on the surface, and where physical and chemical conditions are conducive to microbial growth, there are microorganisms. Carbon produced by photosynthesis, of which approximately 1×10^{16} moles is synthesised per year (Field et al., 1998; Raven, 2009), leaches into available habitat space and provides energy for microorganisms that use organics as an electron donor for growth, or they ferment. Aerobic organisms use oxygen as an electron acceptor, which is also produced as a waste product of photosynthesis. Thus, the pervasive availability of energy on the Earth leads to the observation that most habitable spaces are colonized (Whitman et al., 1998). Secondly, habitats on the Earth generally display connectivity, both through the widespread presence of liquid water, and thus a hydrological cycle which distributes carbon and microorganisms to newly formed habitats, and the distribution of carbon and microorganisms though the atmosphere.

In this paper, we discuss the significance of uninhabited habitats on Mars, and their implications for the search for life.

2. The Significance of Uninhabited Habitats

If uninhabited habitats are discovered or suggested by robotic craft, what would be their significance to science? Terrestrial biological sciences would learn a substantial amount. For example, geochemical processes on the Earth have been linked to life since the early Archean when sulphur, carbon and iron cycles on the Earth, and other elements, were influenced by microorganisms (Canfield et al., 2006; Sleep and Bird, 2007; Lyons and Gill, 2010). However, we lack a set of abiotic controls with which to develop an insight into the influence and magnitude of these biological contributions. Abiotic and biological influences can sometimes be separated, for example, by investigating fractionation patterns of certain elements (Horita, 2005; Thomazo et al., 2009; Craddock and Dauphas, 2011), but, in the case of iron, for example (Balci et al., 2006), these are not always effective at resolving the biological contribution.

Uninhabited habitats in which geochemical processes occur without biota, but in which the conditions approximate to environments in past or present terrestrial habitats, would offer a new set of controlled comparisons. An example might be the weathering interactions of water with rocks. Weathering rates on Mars have been investigated (e.g. Hausrath et al., 2008). The application of these methods to the study of weathering in uninhabited habitats could provide a better understanding of the rate of chemical reactions at rock-water interfaces without the confounding effects of biology. These insights are vital for improving understanding of the role of abiotic and biotic weathering in the carbonate-silicate cycle on the Earth and more generally in global elemental cycles. Yet another example would be ancient habitable hydrothermal systems on Mars where the study of mineral sequences and deposition could be compared to identical systems in volcanic or impact environments on present-day Earth that contain life, to unravel more completely the effects of biology on hydrothermal mineral deposition and chemistry, thus improving our understanding of the role of biota in extreme environment biogeochemistry.

From an astrobiological perspective, the search for uninhabited habitats on Mars is an essential task in understanding what controls the distribution of life in the Universe and what conditions limit its distribution. For example, based on the empirical observation that all life on Earth is linked to the presence of liquid water, it is widely assumed that where there is liquid water, there is life. Although water is a necessary requirement for life, the presence of water in habitable conditions does not imply the presence of life. The assumption that it does is embedded within the wider assumption that where there are habitats there will be life, an inductive inference based on empirical observation that this is the case for most environments on the Earth.

Both of these generalizations are driving the search for life beyond Earth, especially in the case of Mars (Irion, 2002; Hubbard et al., 2002; Mottl et al., 2007; Jones and Lineweaver, 2010). However, there are several plausible scenarios by which uninhabited habitats might exist on Mars, and they need to be considered as likely outcomes of our exploration of the planet. These scenarios are derived from the categorisation in Cockell (2011), ignoring the one that is not relevant to the search for life (a planet that is too young for an origin of life, but where habitable environments exist), and are explored in detail below. Finding uninhabited habitats on Mars would not be considered a negative result or a strategic failure. On the contrary, such a finding would have profound relevance to our understanding of life in the Universe.

Finally, the discovery of extant uninhabited habitats on Mars would have implications for planetary protection. The discovery of abundant uninhabited habitats on Mars would suggest either that Mars is lifeless, or if it is inhabited, then there is a lack of connectivity between available habitats. These conclusions might suggest that planetary protection requirements could be dramatically relaxed. However, the introduction of life into an extant uninhabited habitat by an unsterilized spacecraft would represent a type of destructive sampling since future searches for life would need to avoid previously studied, but now contaminated, uninhabited habitats.

By contrast, since an extant uninhabited habitat might achieve connectivity with inhabited regions with an unknown probability, from a position of prudence they might be included within Mars 'Special Regions' (Kminek et al., 2010). Steps might be taken to prevent their contamination to avoid losing the scientific value that these habitats can provide and to reduce the probability of contaminating inhabited regions should a connection between the uninhabited habitat and potentially inhabited habitats occur.

3. Uninhabited Habitats in the Solar System

Uninhabited habitats are extremely rare on the Earth, but a few examples must be noted. One way to obtain an uninhabited habitat on the Earth is for an inhabited environment to be separated from the surface photosynthetic biosphere, sterilized and then for it to remain disconnected from the surface. One location where they can occur is the deep subsurface. There is some evidence for such habitats. An example is oils that have been sterilized in the deep subsurface and then cooled, for example in the Peace River and Athabasca tar sands in Alberta, Canada (Wilhelms et al., 2001; Adams et al., 2006; Larter et al., 2006), or deep-subsurface materials sterilized by an asteroid or comet impact and subsequently cooled (Cockell et al., 2009).

Uninhabited habitats on the Earth can potentially exist transiently where a geological disturbance occurs, producing a new, sterile substrate. A molten volcanic lava flow will eventually cool to below the upper temperature limit for life. There is likely to be a period between the instant at which the temperature drops below this limit and the instant at which the first microorganism land on the rock (Brock, 1973; Weber and King, 2010) and begins to be metabolically active. During this brief period the environment will be an uninhabited habitat and constitutes the very first stage of ecological primary succession. In most situations this period will be short because of the presence of airborne or waterborne microorganisms, which are delivered rapidly onto the surface of such substrates. However, the interior of the substrate, for example the inside of newly formed, but vesicular volcanic rocks, may well remain uninhabited for longer than the surface environment.

Newly arrived meteorites on the surface of the Earth, in the period between their fall and their contamination by a terrestrial biota, are also transient uninhabited habitats.

Although uninhabited habitats are rare on the Earth, they may be more common on other planetary bodies. Subsurface oceans of icy moons such as Europa (Marion et al., 2003; Hand et al., 2007) and Enceladus (Parkinson et al., 2008; McKay et al., 2008) are examples of candidate uninhabited habitats, although we do not know enough about the physicochemical conditions within their putative oceans and/or subsurface water bodies to know if they are habitable – or in fact, inhabited. In the coming decades, the study of extrasolar planets (Léger et al., 1993; Wolstencroft and Raven, 2002; Segura et al., 2005; Turnbull, 2008; Kaltenegger and Selsis, 2009) may provide potential candidate habitable, but uninhabited planets.

Of all planetary bodies in the Solar System, Mars shares the most similarities with Earth, particularly as we retreat back in time, when conditions on the surface of the planet allowed for the existence of lakes, rivers and other aqueous environments. This, combined with a long-lasting active volcanism, and an intense impact history, increases the possibility of habitat development on Mars, compatible with life.

4. Uninhabited Habitats on Mars

Uninhabited habitats on Mars, and uninhabited habitats generally, can be split into two categories: 1) A Mars devoid of life, but which has available habitats; and 2) A Mars with life, but that possesses localised uninhabited habitats. At the time of writing we do not know if Mars is inhabited, so the planet could fall into either one of these categories. In each category the uninhabited habitats themselves are qualitatively similar (i.e. locations in which life could exist, but does not), the distinction is in the *reasons* for the existence of the uninhabited habitats. In the first category, uninhabited habitats exist because there is no life at all to take advantage of them; in the second category habitats are uninhabited because the life on the planet is unable to access them.

We have numbered each scenario which might lead to uninhabited habitats (Figure 2) and discuss each of them below.

4.1. Uninhabited Habitats on an Uninhabited Mars

There are four possible scenarios that could lead to the presence of uninhabited habitats on an uninhabited Mars:

1. ***The origin of life is rare.*** Mars might have possessed habitable conditions for life, but life never originated to take advantage of the conditions available because the origin of life is an unusual event with a low statistical probability of occurring (Lal, 2008, Chela-Flores, 2007). We do not know enough about the origin of life to assess this possibility quantitatively with origin of life experiments (Cairns-Smith, 1982; Russell and Arendt, 2005; Brack, 2007; Raulin, 2007). This scenario would be difficult to demonstrate until all of Mars had been comprehensively explored for the presence of life, past and present. For example, habitable conditions in ancient Noachian terrains that were exposed to water, but possess no evidence of past life, could have been permanently separated from inhabited regions in the deep subsurface. To demonstrate the scenario of a lifeless planet hosting uninhabited habitats would require definitive demonstration that there is no life anywhere on Mars.

This scenario assumes that life is not transferred into Martian uninhabited habitats from Earth (Clark, 2001; Horneck et al., 2001a; Stöffler et al., 2007; Cockell, 2008). All the scenarios for the presence of uninhabited habitats on an uninhabited Mars must assume that the uninhabited habitats remain biogeographically isolated from the Earth.

The transfer of life from one planet to another in rocks (lithopanspermia) ejected by asteroid and comet impacts has not been demonstrated. However, the survival of microorganisms in impact shock experiments (Horneck et al., 2001b; Burchell et al., 2001, 2004), their longevity in space (Horneck et al., 1994) and low temperatures within meteorites that have landed on the Earth, suggesting internal rock environments allowing organisms to survive atmospheric transit (Fajardo-Cavaros et al., 2005) might suggest a plausible transfer mechanism for life from Earth to Mars. Certainly rocks have been transferred between the two planets (Gladman et al., 1996; Mileikowsky et al., 2000). Even if the transfer of life from Earth to Mars occurred, local habitats might remain uninhabited even under a scenario of active lithopanspermia. To assess this possibility would require more insight into whether lithopanspermia between Earth and Mars has occurred and if it has, what the spatial distribution of terrestrial organisms would be on the surface and subsurface of Mars from this process.

2. ***The conditions for the origin of life did not exist.*** The origin of life might require some prebiotic reactions to occur in very different conditions than those suitable for life, for example in the interior of deep ocean hydrothermal vents, well above the upper temperature limit for life (Holm, 1992; Huber and Wächterhäuser, 1997; Rushdi and Simoneit, 2001). If such environments did not exist on Mars, then we could imagine that conditions could be suitable for life, but local environments were never satisfactory for life to originate. On Mars, acidic groundwater conditions during the Noachian (Squyres and Knoll, 2005) might have precluded the origin of life, allowing for uninhabited habitats. This scenario also assumes that life is not transferred into uninhabited habitats from Earth, similarly to the previous scenario.

3. ***The conditions for the origin of life existed, but they were too transient***. A planet with fluctuating environmental extremes might possess transient conditions suitable for the origin of life and its propagation, but their duration is too short to allow for the emergence of life.

On Mars, if early conditions were broadly hostile to an origin of life, acceptable conditions for the origin of life may have come and gone without an origin of life occurring. We know too little about the environments in which an origin of life can occur to know whether uninhabited habitats might have existed on account of this scenario. This scenario again assumes that life is not transferred into uninhabited habitats from Earth.

*4. **Life originated, but a cataclysm wiped out life and it never became re-established despite the planet subsequently being favourable for life**.* An early Martian cataclysm is predicted from models (Gomes et al., 2005) and age determinations of meteorites and lunar rocks (Cohen et al., 2000). The latest model of planetary orbital movements, asteroid population and asteroid trajectory changes inferred from the planetary movements predicts that on Earth 15±4 basin-sized and 30±5 Chicxulub-sized impact structures were formed within about 400 My during Late Heavy Bombardment in the Earth's Archean (Bottke et al., 2011). Likewise, Noachian Mars would have been hit - to the extent that it might have been driven out of an originally circular orbit (Bottke et al., 2011). If existing life had been terminated by the Late Heavy Bombardment, leaving the entirety of Mars sterile, this would also require that life did not originate again (which could result from the scenarios described in 1 to 3 above) and that there was no re-establishment of life from surviving organisms in space (Wells et al., 2003; Gladman et al., 2005). As for the Earth, it might be that even very heavy bombardments would leave deep-subsurface refugia where life could have persisted (Sleep and Zahnle, 1998; Abramov and Mojzsis, 2009).

4.2. Uninhabited Habitats on an Inhabited Mars

Uninhabited habitats could exist on an inhabited Mars. There are four circumstances which would lead to these environments. In the first three of these scenarios, the longevity of an uninhabited habitat on present-day Mars would be expected to be much greater than on the present-day Earth because: 1) there is no large scale photosynthetic biosphere to generate carbon and oxygen distributed on a planetary scale to fuel organisms in newly formed habitat space, and 2) there is not the same extent of connectivity between environments, either through the hydrological cycle, or through the much more biologically detrimental atmosphere. On early Mars, liquid water was more prevalent, which might have improved hydrological connectivity between environments.

1. ***Inhabited habitats become sterilised and cut off from other inhabited regions, rendering them uninhabited.*** Subsurface examples of this category exist on the present-day Earth, as discussed earlier. On Mars, asteroid and comet impacts could create sterilized near-surface conditions that remain disconnected from biota on the planet.

2. ***Habitable environments become available, but they are too transient to be colonized.*** An example could be Martian periglacial terrains in which near-surface ice melted as a result of climate fluctuations (e.g., Balme and Gallagher 2009). Other permafrost regions that do not undergo cyclical thaw could also be subject to occasional melting, for example in small asteroid and comet impacts, which could provide a short-lived liquid water habitat that might be too short-lived for colonization to occur. For example, a hypothetical scenario (Figure 3) is a subsurface Mars where a biota lives within deep fractures and aquifers. However, a lack of connection with the surface environment; the hostile, desiccating environmental conditions, which prevent atmospheric transport of organisms, and the lack of liquid water movement on the surface connecting the newly-formed habitat to inhabited regions, could render a new liquid water habitat uninhabited for its duration of its existence.

3. ***New sterile materials are formed by geological processes such as asteroid and comet impacts and volcanic eruptions.*** These environments are different from those in (2) in which the habitat is transient. In this scenario the habitat is long-lived. These materials experience a period when they are habitable, but uninhabited. Examples on the Earth include new lava

flows. Although the period of being uninhabited is usually short on the Earth because of the connectivity of new habitats with inhabited habitats through the atmospheric and waterborne transport of microorganisms, the period of being uninhabited on Mars could be very large and may be equal to the lifetime of the habitat itself.

4. ***Habitats are available, but the biochemical systems required to deal with the physical or chemical characteristics within them have not yet evolved.*** On Mars, a speculative scenario that would fit this category would be a surface hydrothermal system which was uninhabitable to organisms from a deep subsurface biosphere that were unadapted to high UV and ionizing radiation, periodic desiccation on the Martian surface etc.

5. The SNC (Martian) meteorites – Evidence for Uninhabited Habitats?

Empirical evidence for uninhabited habitats might be sought in Martian meteorites collected on the Earth. Of these, there are eight meteorites grouped as the nakhlites, and these are olivine-clinopyroxene cumulates which formed at ~10-100 m depth from the Mars ground surface, in a thick lava flow or intrusion (e.g. Bridges and Warren, 2006; Treiman, 2005; Lentz et al., 1999). The nakhlites have secondary alteration products (Bridges et al., 2001) that suggest their alteration in a neutral hydrothermal system with temperatures less than 150 °C. Iron carbonate, iron phyllosilicate (smectite and serpentine) and an amorphous silicate gel are present in veins and within the mesostasis of the nakhlites (Bridges et al. 2001; Changela and Bridges, 2010). Ten percent of the olivine in the Lafayette nakhlite – assumed to be the sample nearest the fluid source at the base of the nakhlite pile – is composed of fracture-filled secondary veins, with an average width of 15 µm. K-Ar dating (Swindle et al., 2000) suggest that this alteration occurred ≤670 Ma ago and so at a relatively recent time in Mars' history.

Different nakhlites allow for a model of a putative, short-lived, rapidly cooled, hydrothermal system to be developed (Changela and Bridges, 2010). The rapid cooling as evidenced by the metastable and sometimes amorphous assemblages, suggest rapid heating and cooling in a short-lived event, probably associated with impact melting of buried ice. This fluid percolated upwards through the nakhlite pile, with limited compositional fractionation e.g. Mg/Mg+Fe ratio of the silicate gel, and was terminated by evaporation of soluble salts.

The presence of liquid water in circulation with ultramafic rocks is potential evidence for a habitat. Some workers have reported martian organics within the Nakhla meteorites and hypothesised that they are the remnants of Martian biology (Gibson et al., 2006; McKay et al., 2011). If this hypothesis is eventually accepted, then the hydrothermal system was inhabited. The null hypothesis is that the nakhlite secondary minerals are candidates as uninhabited habitats.

ALH84001 is a cumulate orthopyroxenite which crystallised 4.5 Ga and is thus a fragment of the Noachian crust (Nyquist et al., 2001). It contains ~1 vol% Ca-Mg carbonate rosettes which are up to 250 μm size (Mittlefehldt, 1994). These have been dated at ~4 Ga (Turner et al., 1997; Corrigan and Harvey, 2004). The majority of the research into this carbonate has concluded that the rosettes formed at low temperature e.g. <100 ^{o}C (e.g. Van Berk et al., 2011). The near neutral fluid resulted from isochemical alteration of the surrounding orthopyroxenite and cooled rapidly e.g. within months to produce metastable carbonate assemblages (Bridges et al. 2001). These carbonates have famously and provocatively been attributed to the discussion of martian biological activity (McKay et al., 1996). The key evidence was morphological e.g. bacteria-like shapes observed on mineral surfaces and the morphology of magnetite grains on the carbonate rosette rims. The biogenic interpretation has been challenged. For instance, the magnetite rims have been attributed to shock-induced alteration of the carbonate (Brearley, 1998; Bradley et al., 1998). Thus a 'null' hypothesis for the ALH84001 carbonates is that they represent the mineral constituents of an uninhabited habitat.

6. Testing the Hypothesis 'where there are habitats, there is life' on Mars

The association of life with available habitats can be turned into a generalised hypothesis: 'where there are habitats, there is life', which is falsifiable by demonstrating the presence of an uninhabited habitat in the location under study. The hypothesis is experimentally testable on Mars by using robotic craft or human explorers *in situ* to investigate the chemistry/organic chemistry of selected environments that are thought to be, or could have been, conducive to life, or by examining the interior of rocks and other materials returned to the Earth in Mars Sample Return (MSR). A demonstration of the presence of an uninhabited habitat would be to identify an environment with two characteristics: 1) By all available criteria, the environment is or was habitable: i.e. it contains or contained liquid water, a plausible energy source, nutrients, appropriate physicochemical conditions, 2) There are no associated organics or organic signatures that suggest the presence of a biota to take advantage of the habitat during the period it is proposed to be an uninhabited habitat. An uninhabited habitat could contain meteoritic-derived organic carbon (Sephton, 2002), but it should not contain organics associated with metabolically active life.

An uninhabited habitat could contain signatures of inactive life (for example dormant cells unable to grow in the environment that have been entrained from an inhabited location somewhere else). On Mars, the distinction between a habitat containing active life (an inhabited habitat) and an uninhabited habitat containing inactive life would be moot in the early stages of exploration, since either case would constitute the discovery of life. However, the distinction would be important in attempting to identify other locations on Mars where life might be found or where it can propagate. There are obviously technical microbiological complications in separating an inhabited habitat from an uninhabited habitat containing inactive life that turn on the ability to show that the organisms are active.

The interpretation of data must be approached with caution because experimental measurements might misinterpret an uninhabited habitat for a place that is actually uninhabitable. Three potential misinterpretations could occur:

1) An element essential for life might be missing. However, we know enough about the required elements for life (i.e. C,H, N,O, P, S) and life's requirement for water to make reasonable assessments of the habitability of different environments that are examined (Stoker et al., 2010). If these habitats are in contact with volcanic rocks, then other elements (Mg, Ca, Na, K, P, S, Ni, Zn, etc) are likely to be available to life. The suite of elements in an environment can be determined quite comprehensively by such methods as X-Ray Fluorescence, X-Ray Diffraction, Raman and LIBS (Laser-Induced Breakdown Spectroscopy).

2) There are elements or compounds present which are detrimental to life, but which remain undetected. Although entirely novel toxic compounds that remain undetected cannot be ruled out, the discovery of perchlorate (Hecht et al., 2009) shows how modern chemical analytical approaches can successfully characterise Martian environments, even with respect to unexpected chemicals. Nevertheless, new laboratory experiments to study the effects of the environment on life might be required in the light of physico-chemical measurements revealing the presence of unexpected chemicals.

3) Toxic compounds might have existed in past environments but are now no longer present. It is difficult to rule out this possibility, but the characterisation of the geochemistry of a given Martian environment in the context of surrounding environments can provide a comprehensive understanding of its past chemical composition.

Other factors that influence habitability can also be assessed by robotic craft or sample return. For instance, fractures and pore spaces within rocks are likely to provide sheltered microenvironments where water availability might be improved or temperatures ameliorated compared to macroclimatic conditions. These can be quantified using microscopic imagers that allow for a more complete assessment of a microenvironment as a habitable space. Radiation instruments can be used to quantify the radiation *in situ* impinging on an environment and theoretical models can then be executed to calculate the radiation environment within a given putative habitat space. Known microbial tolerances to these inferred radiation regimens can then be used to assess whether the microenvironment is habitable. Thus, spacecraft observations coupled to modelling and microbiological data can be employed to assess whether an environment is an uninhabited habitat.

The determination of whether the environment supported life can be approached by a search for organics or remains of life using a wide variety of analytical methods such as GC-MS, fluorescence, or lab-on-a-chip approaches.

The detection of uninhabited habitats would greatly constrain conclusions about the presence of life on past or present Mars. Today, the surface of Mars is cold, dry, and exposed to sterilising doses of UV and ionising radiation. For that reason it is assumed to be uninhabitable. This supposition still needs to be demonstrated on a planetary scale, and so far it is only supported by results from the Viking landers, which searched for metabolically active life in soils, but failed to find conclusive evidence for it. From a programmatic and budgetary perspective, it would not be practical to search all the surface of Mars for life. Uninhabited habitats might play a significant role in resolving this limitation. If carefully selected environments on the surface or the subsurface of Mars (i.e. environments likely to have been habitable in the recent past) are found to be uninhabited, then we might more confidently conclude that life is absent on present-day Mars, without having to explore the whole planet. Similarly, if environments thought to have been habitable early in the history of the planet do not contain any traces of past biological activity, we might more confidently conclude that the surface of Mars has not been inhabited for most of its history. In both of these cases, though, the hypothetical scenario in which life is present in some locations, but biochemical adaptations have not evolved to allow it to colonize places considered to be habitable from a terrestrial perspective, would have to be considered as a possible explanation.

7. Candidate Uninhabited Habitats

Uninhabited habitats could have existed at any time during Mars' history. They include potentially habitable environments in the water-rich past of Mars (Noachian lakes, impact crater hydrothermal systems, river systems etc.) and present-day or recent environments containing liquid water. Here we describe some examples of potential uninhabited habitats:

7.1 Recent or Present-Day Uninhabited Habitats

Habitats in the frozen polar regions.

Very young uninhabited habitats could have been created as a result of the ~100 ka cyclical variations in Mars' obliquity (Laskar et al. 2004). Jakosky et al. (2003) examined the conditions required to melt Martian polar ice in the past and concluded that during periods of higher obliquity (>40°), average temperatures could have risen above -20 °C, creating conditions for the melting of Martian polar ices, producing habitable environments. Such obliquity conditions have occurred within the last few million years (Laskar et al. 2004). Any liquid-water containing habitable environments produced by past obliquity changes are potential uninhabited habitats. Melting of ice under different obliquity conditions has been associated with many recent martian landforms in both polar and non-polar regions, including periglacial terrains (Balme and Gallagher 2009, Gallagher et al. 2011), fluvial-like gullies (Costard et al. 2002) and thermokarst-like depressions (Soare et al. 2008).

Stoker et al. (2010) provide a detailed habitability assessment for the Phoenix landing site in the Martian northern polar region and conclude that it has the highest habitability probability of any of the Martian landing sites so far examined. Nutrient sources, including C, H, N, O, P and S compounds were identified. Energy sources could be sunlight or chemical energy. The presence of perchlorate suggests the potential for lowered freezing point solutions, although conductivity measurements did not record liquid water and perchlorate may be detrimental to life. However, periods of high obliquity might allow for transient liquid water to form (Zent, 2008; Stoker et al., 2010), generating short-lived uninhabited habitats.

Mars analogue environments on Earth provide clues to possible recent habitats on Mars. For example, in terrestrial polar glacial systems, debris-rich ice layers are common even where basal ice temperatures are as low as -17 ^{o}C (Cuffey et al., 2000; Samyn et al., 2005). The basal ice layers are characterized by alternating layers of debris-poor and debris-rich ice, similar to the North Polar Basal Unit (BU) on Mars. The increased surface area of fine-grained material in the basal ice debris is effective in trapping thin water films that are liquid significantly below 0 ^{o}C (Price, 2007) and, combined with the ground-up mineral material, potentially provide significant energy sources and nutrients for microbial activity (Skidmore et al., 2000). Miteva et al. (2009) demonstrated cell counts at least two orders of magnitude higher in the debris-rich ice layers than the clean ice layers, and debris-rich layers can harbor obligately anaerobic organisms such as methanogens (Skidmore et al., 2000).

Habitats in dry equatorial regions

With respect to drier regions on Mars, such as the equator and mid-latitudes, the Atacama Desert in Chile, serves as a useful case-study. The main limiting factor for life in the Atacama is aridity. The low precipitation rates make the soil inhospitable, and it has been suggested that the extreme aridity of the core region of the Atacama causes the development of "Mars-like soils" (Navarro-Gonzalez et al., 2003), which share similarities with soils analysed by the Viking landers. Despite the extremely dry conditions and the low concentrations of organics in the soils, microorganisms are present (Connon et al., 2007; Lester et al., 2007), perhaps in isolated islands of bacteria-rich soil (Bagaley, 2006). However, the presence of cells does not imply that the soils are habitable. In fact, microbial activity in soils of the most arid regions of the Atacama Desert has not yet been demonstrated.

An abundant and diverse microbial community has been described in the interior of salt knobs found within the same arid core region where "Mars-like soils" occur (Wierzchos et al., 2006; de los Rios et al., 2010). These salt knobs are colonized by photosynthetic and heterotrophic bacteria and archaea. These organisms take advantage of the hygroscopic properties of the salt, which result in the condensation of liquid water directly from the atmosphere at the deliquescence point of the salt (Davila et al., 2008). Based on these studies, it has been proposed that as environments become increasingly drier, life seeks refuge in habitats that provide marginal amounts of water such as the interior of hygroscopic salts, and that such substrates could have been habitable environments on Mars (Davila et al., 2010).

As one moves to slightly wetter (but still very dry) regions of the Atacama, new habitats evolve such as the surface and interior of porous and translucent gypsum crusts (Wierzchos et al., 2011). In still wetter regions, the hypolithic habitat (life under translucent rocks), largely absent in the drier regions, becomes available (Warren-Rhodes et al., 2006). A humidity transect along the Atacama Desert provides some constraints on the sorts of habitats (hygroscopic salts, the interior of porous and translucent rock, the underside of rocks, and soils) that might be sites for the investigation of potentially uninhabited habitats on Mars.

7.2 Past Uninhabited Habitats

Hot and hydrous habitats: Impact craters and volcanoes

In the early history of Mars there is a diversity of candidate uninhabited habitats. Of those, impact craters are high priority places for the search for habitats, because a diversity of processes, and therefore environments, is concentrated in a small space. First, an impact that hits a water-bearing Martian target causes a series of changes in the target environment. The energy deposited causes compression, deformation, fracturing and the formation of the crater itself (e.g., Melosh, 1989). Following crater formation, the target rocks are hot, in large impact structures impact-melt and melt breccias occur. The temperature gradient between centre of impact and the colder surroundings will initiate a hydrothermal system in the target rock (Newsom, 1980; Rathbun and Squyres, 2002; Abramov and Kring, 2005), even if the target is frozen (Barnhardt et al., 2010; Ivanov and Pierazzo, 2011). The impact-generated hydrothermal system might cause alteration, e.g. the formation of serpentine, chlorite, smectite and other hydrous alteration phases (Schwenzer and Kring, 2009). Moreover, the dissolution of the target rock is capable of liberating elements such as Ca or Mg from the host rock, and producing H_2 in an ultramafic target (Zolotov et al., 2004; Schwenzer, 2011). All of those products could provide nutrients and energy sources for life (Varnes et al., 2003).

To illustrate the importance of Martian impact-generated hydrothermal systems for habitability, Toro Crater is an excellent example. Marzo and coworkers (Marzo et al., 2010) have provided a detailed investigation of this Hesperian crater, which is located at 71.8°E, 17.0°N on the western edge of Isidis Basin. Its age is estimated to be 3.6±0.1 Ga, but resurfacing events have created younger surfaces within the crater. Its central uplift exhibits brecciated target rock, and clast-poor and clast-rich impact melt deposits. Two features indicate the presence of post-impact generated hydrothermal activity: vent structures and hydrated silicates occurring in and around the central uplift structure. The vent structures surround the central uplift on its eastern side. The alteration minerals occur in discrete areas in and around the central mound. Marzo and coworkers map prehnite, opaline, smectite, and chlorite. The existence of such minerals changes the subsurface environment beyond the period of (transient) water activity, because water storage and ion exchange capability are introduced, enhancing the habitability of the site. Thereafter, the geologic processes at Toro Crater are restricted to sparse sedimentation depositing crater wall material in the crater moat and additional eolian influx (Marzo et al., 2010). In summary, cratering creates a variety of habitable sites all within the limited area of the crater itself, which opens up multiple possibilities for exploration to find potential habitats, and then explore them to discover if they were uninhabited or inhabited.

Volcanoes provide many of the same features, illustrated by the Tharsis volcanic region (Dohm et al., 2008), for which Schulze-Makuch et al. (2007) list a variety of target sites for the exploration of endogenic-hydrothermal systems. Channel networks promoted by the topography, heated subsurface water, and potentially precipitation, provide further conditions for the development of habitable environments. Unlike impact crater cavities, volcanoes do not offer the same potential for water catchment, but they provide topographic highs that could enhance precipitation and thus surface water availability to uninhabited habitats, a process that might be ongoing on present-day Mars (Maltagliati et al., 2007).

Martian sediments

OMEGA (*Mars Express*) and CRISM (*Mars Reconaissance Orbiter* MRO) spectrometers have found widespread evidence of water/rock interaction in the ancient highlands, with hydrous minerals found within craters, or possibly associated with impact processes. The hydrated silica/altered glass, zeolite, chlorite and smectite within impact craters are evidence of aqueous alteration (Mustard et al., 2008; Ehlmann et al., 2009). Other ancient Mars features indicate persistent standing water, such as Eberswalde Delta imaged by MRO and CRISM (Moore et al., 2003). The foresets of the Eberswalde Delta contain phyllosilicates (McKeown et al., 2011). Such deposits may in turn be related to impacts events (Irwin, 2011). Moreover, the post-impact history of large impact-craters can include the formation of a crater lake (Newsom et al., 1996; Newsom, 2010). Water from a hydrothermal system might be discharged and groundwater might flow in. The lake, while a habitat in itself, might produce sediments and mineral precipitation, creating additional, new habitable places. One example for an impact crater with an extended post-impact hydrous activity is Gale Crater (Cabrol et al., 1999). This crater might have been filled by water inflow from the north and hosted a standing body of water for over two billion years (Cabrol et al., 1999). Jezero Crater, located south of Nili Fossae, can be seen in context with the above mentioned Eberswalde Crater Delta, because it, too, hosts deltaic deposits. Those contain phyllosilicates which are interpreted to be sourced from the Nili Fossae region and have high preservation potential for organic material (Ehlmann et al., 2008). Thus, impact lakes, lake deposits and fluviatile sediments in crater catchments offer additional habitats that could be plausible candidates for the search for uninhabited habitats.

Other ancient sediments deposited from water have also been described on Mars by the *Opportunity* Lander. The festoon-bedded sequence that the rover encountered is believed to have formed in an ephemeral, playa lake-type environment (Grotzinger et al., 2005). A significant proportion of the layered deposits imaged in the ancient highlands by high resolution cameras from *Viking* onwards may consist of aqueous-formed deposits and may be candidate uninhabited habitats.

Summary

There is a diversity of scenarios on an inhabited or uninhabited Mars that would create conditions for uninhabited habitats. The possibility of near-surface transient liquid water is the most plausible scenario for uninhabited habitats on the present-day or in recent history of Mars, but in its past Mars might also have hosted these habitats in environments including craters and volcanic regions. Martian meteorites might provide empirical evidence for uninhabited habitats, but *in-situ* exploration and sample return will also allow for the elucidation of their existence. Uninhabited habitats would tell us much about the role of biology in shaping planetary geochemical processes, but they would also raise new questions in planetary protection.

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References

Abramov, O., Kring, D.A., 2005. Impact-induced hydrothermal activity on Early Mars. Journ Geophys Res.110 (E12S09).

Abramov, O., Mojzsis, S.J., 2009. Microbial habitability of the Hadean Earth during the late heavy bombardment. Nature 459, 419-422.

Adams, J., Riediger, C., Fowler, M., Larter, S., 2006. Thermal controls on biodegradation around the Peace River tar sands: paleo-pasteurization to the west. Journ Geochem Explor 89, 1-4.

Bagaley, D.R., 2006. Uncovering bacterial diversity on and below the surface of a hyper-arid environment, the Atacama Desert, Chile. PhD thesis, Louisiana State University, Baton Rouge, LA.

Balci, N., Bullen, T.D., Witte-Lien, K., Shanks, W.C., Motelica, M., Mandernack, K.W., 2006. Iron isotope fractionation during microbially stimulated Fe(II) oxidation and Fe(III) precipitation. Geochim Cosmochim Acta 70, 622-639.

Balme, M.R., Gallagher, C., 2009. An equatorial periglacial landscape on Mars. Earth Planet Sci Lett 285, 1-15.

Barnhart, C.J., Nimmo, F., Travis, B.J., 2010. Geochemical and geomorphological effects on post-impact hydrothermal systems incorporating freezing. Icarus 208, 101–117.

Battistuzzi, F.U., Hedges, S.B., 2009. A major clade of prokaryotes with ancient adaptations to life on land. Mol Biology Evol 26, 335-343.

Bottke, W.F., Vokrouhlický, D., Minton, D., Nesvorný, D., Morbidelli, A., Brasser, R., Simonson, B., 2011. The Great Archean Bombardment, of the Late Heavy Bombardment. 42nd Lunar and Planetary Science Conference, # 2591.

Bosakowski, T., Smith, D.G., 1997. Distribution and species richness of a forest raptor community in relation to urbanization. J Raptor Res 31, 26-33.

Brack, A., 2007. From interstellar amino acids to prebiotic catalytic peptides: A review. Chemistry and Biodiversity 4, 665-679

Bradley, J.P., McSween, H.P., Harvey, R.P., 1998. Epitaxial growth of nanophase magnetite in Martian meteorite Allan Hills 84001: Implications for biogenic mineralization. Met Planet Sci 33, 765–773.

Brearley, A.J., 1998. Magnetite in ALH84001: product of the decomposition of ferroan carbonate. 29th Lunar and Planetary Science Conference, #1451.

Bridges, J.C., Catling, D.C., Saxton, J.M., Swindle, T.D., Lyon, I.C., Grady, M.M., 2001. Alteration assemblages in the Martian meteorites: Implications for near-surface processes. In: Chronology and evolution of Mars. Kallenbach, R., Geiss, J., Hartmann, W.K. Kluwer: Dordrecht. pp. 365–392.

Bridges, J.C., Warren, P.H., 2006. The SNC meteorites: Basaltic igneous processes on Mars. Journ Geological Society London 163, 229–251.

Brock, T.D., 1973. Primary colonization of Surtsey, with special reference to the blue-green algae. Oikos 24, 239-243.

Burchell, M.J., Mann, J.R., Bunch, A.W., Brando, P.F.B., 2001. Survivability of bacteria in hypervelocity impact. Icarus 154, 545-547.

Burchell, M.J., Mann, J.R., Bunch, A.W., 2004. Survival of bacteria and spores under extreme shock pressures. Monthly Notices Royal Astronom Soc 352, 1273-1278.

Cabrol, N.A., Grin, E.A., Newsom, H., Landheim, R., McKay, C.P., 1999. Hydrogeologic Evolution of Gale Crater and Its Relevance to the Exobiological Evolution of Mars. Icarus 139, 235–245.

Cairns-Smith, A.G., 1982. Genetic take-over and the mineral origins of life. Cambridge, Cambridge University Press.

Canfield, D.E., Rosing, M.T., Bjerrum, C., 2006. Early anaerobic metabolisms. Phil Trans Royal Soc 361, 1819-1836.

Chase, J.M., Leibold, M.A., 2003. Ecological Niches: Linking Classical and Contemporary Approaches. Chicago, University of Chicago Press.

Changela, H., Bridges, J.C., 2010. Alteration assemblages in the nakhlites: variation with depth on Mars. Met Planet Sci 45, 1847-1867.

Chela-Flores, J., 2007. Testing the universality of biology: a review. Int Journ Astrobiol 6, 241-248.

Clark, B.C., 2001. Planetary interchange of bioactive material: Probability factors and implications. Origin Life Evol Biosph 31, 185-197.

Cockell, C.S., 2009. The interplanetary exchange of photosynthesis. Origin Life Evol Biosph 38, 87-104.

Cockell, C.S., 2011. Vacant habitats in the Universe. Trends Ecol Evol 26, 73-80.

Cockell, C.S., Gronstal, A.L., Voytek, M.A., Kirshtein, J.D., Finster, K., Sanford, W.E., Glamoclija, M., Gohn, G.S., Powars, D.S., Wright Horton, J. Jr., 2009. Microbial abundance in the deep subsurface of the Chesapeake Bay impact crater: Relationship to lithology and impact processes. Geological Society of America Special Papers 458, 941-950.

Cohen, B.A., Swindle, T.D. & Kring, D.A., 2000. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. Science 290, 1754-1756.

Connon, S.A., Lester, E.D., Shafaat, H.S., Obenhuber, D.C., Ponce, A., 2007. Bacterial diversity in hyperarid Atacama Desert soils. Journ Geophys Res 112, G04S17.

Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent Martian debris flows by melting of near-surface ground ice at high obliquity. Science 295, 110-113.

Corrigan, C.M., Harvey, P., 2004. Multi-generational carbonate assemblages in Martian meteorite Allan Hills 84001: implications for nucleation, growth, and alteration. Met Planet Science 39, 17–30.

Craddock, P.R., Dauphas, N., 2011. Iron and carbon isotope evidence for microbial iron respiration throughout the Archean. Earth Planet Sci Lett 303, 121-132.

Cuffer, K.M., Conway, H., Gades, A.M., Hallet, B., Lorrain, R., Severinghaus, J.P., Steig, E.J., Vaughn, B., White, J.W.C., 2000. Entrainment at cold glacier beds. Geology 28, 351-354.

Davila, A.F., Gomez-Silva, B., de los Rios, A., Ascaso, C., Olivares, H., McKay, C.P., Wierzchos, J., 2008. Facilitation of endolithic microbial survival in the hyper-arid core of the Atacama Desert by mineral deliquescence. Journ Geophys Res 113, doi:10.1029/2007JG000561.

Davila, A.F., Skidmore, M., Fairén, A.G., Cockell, C.S., Schulze-Makuch, D., 2010. New priorities in the robotic exploration of Mars: the case for in situ search for extant life. Astrobiology 10, 705-710.

de Los Ríos, A., Valea, S., Ascaso, C., Davila, A., Kastovsky, J., McKay, C.P., Gómez-Silva, B., Wierzchos, J., 2010. Comparative analysis of the microbial communities inhabiting halite evaporites of the Atacama Desert. Int Microbiol. 13, 79-89.

Dohm, J.M., Anderson, R.C., Barlow, N.D., Miyamoto, H., Davies, A.G., Taylor, G.J., Baker, V.A., Boynton, W.V., Keller, J., Kerry, K., Janes, D., Fairén, A.G., Schulze-Makuch, D., Glamoclija, M., Marinangeli, L., Ori, G.G., Strom, R.G., Williams, J.P., Ferris, J.C., Rodríguez, J.A.P., de Pablon, M.A., Karunatillake, S., 2008. Recent geological and hydrological activity on Mars: The Tharsis/Elysium corridor. Planet Space Sci 56, 985–1013.

Ehlmann, B.L., Mustard, J.F., Bishop, J.L., Swayze, G.A., Clark, R.N., Poulet, F., Des Marais, D.J., Roach, L.H., Millliken, R.E., Wray, J.J., Barnouin-Jha, O., Murchie, S.L., 2009. Identification of hydrated silicate minerals on Mars using MRO-CRISM: Geologic context near Nili Fossae and implications for aqueous alteration. Journ Geophys Res 114, doi:10.1029/2009JE003339

Ehlmann, B.L., Mustard, J.F., Fassett, C.I., Schon, S.C., Hea,d III J.W., DesMarais, D.J., Grant, J.A., Murchie, S.L., 2008. Clay minerals in delta deposits and organic preservation potential on Mars. Nature Geoscience 1, 355–358.

Fajardo-Cavaros, P., Link, L., Melosh, H.J., Nicholson, W.L., 2005. *Bacillus subtilis* spores on artificial meteorites survive hypervelocity atmospheric entry: implications for lithopanspermia. Astrobiology 5, 726-736.

Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., 1998. Primary production in the biosphere: integrating terrestrial and oceanic components. Science 281, 237–240.

Gallagher, C., Balme, M.R., Conway, S.J., Grindrod, P., 2011. Sorted clastic stripes, Lobes and associated gullies in high-latitude craters on Mars: Landforms indicative of very recent, polycyclic ground-ice thaw and liquid flows. Icarus 211, 458-471.

Gibson, E.K., Clemett, S.J., Thomas-Keprta, K.L., McKay, D.S,, Wentworth, S.J., Robert, F., Verchovsky, A.B., Wright, I.P., Pillinger, C.T., Rice, T., Van Leer, B., 2006. Observation and analysis of in situ carbonaceous matter in Nakhla: part II. 37th Lunar and Planetary Science Conference, #2039.

Gladman, B.J., Burns, J.A., Duncan. M., Lee, P., Levison, H.F., 1996. The exchange of impact ejecta between the terrestrial planets. Science 271, 1387-1392.

Gladman, B., Dones, L., Levison, H.F., Burn,s J.A., 2005. Impact seeding and reseeding in the inner solar system. Astrobiology 5, 483-496.

Gomes, R., Levison, H.F., Tsiganis, K., Morbidelli, A., 2005. Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets. Nature 435, 466–467.

Grotzinger, J.P., Arvidson, R.E., Bell, III J.F., Calvin, W., Clark, B.C., Fike, D.A., Golombek, M., Greeley, R., Haldemann, A., Herkenhoff, K., Jolliff, B.L., Knoll, A.H., Malin, M., McLennan, S.M., Parker, T., Soderblom, L., Sohl-Dickstein, J.N., Squyres, S.W., Tosca, N.J., Watters, W.A., 2005. Stratigraphy and sedimentology of dry to wet eolian depositional system, Burns formation, Meridiani Planum, Mars. Earth Planetary Sci Lett 240, 11-72.

Gudmundsson, F., 1970. Bird migration studies on Surtsey in the spring of 1968. Surtsey Res. Prog. Rep. V:30-39.

Hand, K.P., Carlson, R.W., Chyba, C.F., 2007. Energy, chemical disequilibrium, and geological constraints on Europa. Astrobiology 7, 1006-1022.

Hausrath, E.M., Navarre-Sitchler, A.K., Sak, P.B., Steefel, C.I., Brantlley, S.L., 2008. Basalt weathering rates on Earth and the duration of liquid water on the plains of Gusev Craer, Mars. Geology 36, 67-70.

Hecht, M.H., Kounaves, S.P., Quinn, R.C., West, S.J., Young, S.M.M., Ming, D.W., Catling, D.C., Clark, B.C., Boynton, W.V., Hoffman, J., DeFlores, L.P., Gospodinova, K., Kapit, J., Smith, P.H., 2009. Detection of perchlorate and the soluble chemistry of martian soil at the Phoenix lander site. Science 325:64-67.

Holm, N.G., 1992. Why are hydrothermal systems proposed as plausible environments for the origin of life? Origin Life Evol Biosph 22, 5-14.

Horita, J., 2005. Some perspectives on isotope biosignatures for early life. Chem. Geology 218, 171-186.

Horneck, G., Bücker, H., Reitz, G., 1994. Long-term survival of bacterial spores in space. Adv. Space Res. 14, 41-45.

Horneck, G., Rettberg, P., Reitz, G., Wehner, J., Eschweiler, U., Strauch, K., Panitz, C., Starke, V., Baumstark-Khan, C., 2001a. Protection of bacterial spores in space, a contribution to the discussion on panspermia. Origin Life Evol Biosph 31, 527-547.

Horneck, G., Stöffler, D., Eschwelier, U., Hornemann, U., 2001b. Bacterial spores survive simulated meteorite impact. Icarus 149, 285-290.

Hubbard, G.S., Naderi, F.M., Garvin, J.B., 2002. Following the water, the new program for Mars exploration. Acta Astronautica 51, 337-350.

Huber, C., Wächterhäuser, G., 1997. Activated acetic acid by carbon fixation on (Fe,Ni)S under primordial conditions. Science 285, 245-247.

Irion, R., 2002. Astrobiology science conference: Astrobiologists try to 'follow the water' to life. Science 296, 647-648.

Irwin, R.P., 2011. Timing, duration and hydrology of the Eberswalde Crater Paleolake, Mars. 42nd Lunar and Planetary Science Conference, Abstract #2748; Houston.

Ivanov, B.A., Pierazzo, E., 2011. Impact cratering in H_2O-bearing targets on Mars: Thermal field under craters as starting conditions for hydrothermal activity. Met Planet Sci 46, 601–619.

Jakosky, B.M., Nealson, K.H., Bakermans, C., Ley, R.E., Mellon, M.T., 2003. Subfreezing activity of microorganisms and the potential habitability of Mar's Polar Regions. Astrobiology 3, 343-350.

Jones, E.G., Lineweaver, C.H., 2010. To what extent does terrestrial life 'follow the water'? Astrobiology 10, 349-361.

Kaltenegger, L., Selsis, F., 2009. Characterising extrasolar planets using spectral fingerprints. Comptes Rendus Palevol 8, 679-691.

Kminek, G., Rummel, J.D., Cockell, C.S., R. Atlas, R., Barlow, N., Beaty D., Boynton, W., Carr, M., S. Clifford, S., C.A. Conley, C.A., Davila, A.F., Debus, A., Doran, P., Hecht, M., Heldmann, J., Helbert, J., Hipkin, V., Horneck, G., Kieft, T.L., Klingelhoefer, G., Meyer, M., Newsom, H., Ori, G.G., Parnell, J., Prieur, D., Raulin, F., Schulze-Makuch, D., Spry, J.A., Stabekis, P.E., Stackebrandt, E., Vago, J., Viso, M., Voytek, M., Wells, L., Westall, F., 2010. Report of the COSPAR Mars special regions colloquium. Adv Space Res 46, 811-829.

Lal, A.K. (2008) Origin of Life. Astroph Space Sci 317, 267-278.

Larter, S., Huang, H., Adams, J., Bennett, B., Jokanola, O., Oldenburg, T., Jones, M., Head, I., Riedeger, C., Fowler, M., 2006. The controls on the composition of biodegraded oils in the deep subsurface: Part II – Geological controls on subsurface biodegradation fluxes and constraints on reservoir-fluid property prediction. AAPG Bulletin 90, 921-938.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., Robutel, P., 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. Icarus 170, 343-364.

Lawton, J.H., 1982. Vacant niches and unsaturated communities: a comparison of bracken herbivores at sites on two continents. Journ Animal Ecol 51, 573-595.

Léger, A., Pirre, M., Marceau, F.J., 1993. Search for primitive life on a distant planet : relevance of O_2 and O_3 detection. Astron Astrophys 277, 309-313.

Lekevičius, E., 2009. Vacant niches in nature, ecology, and evolutionary theory: a mini-review. Ekologija 55, 165-174.

Lentz, R.C.F., Taylor, G.J., Treiman, A.H., 1999. Formation of a Martian pyroxenite: A comparative study of the nakhlites and Theo's Flow. Met Planet Sci 34, 919–932.

Lester, E.D., Satomi, M., Ponce, A., 2007. Microflora of extreme arid Atacama Desert soils. Soil Biol Biochem 39, 704-708.

Lyons, T.W., Gill, B.C., 2010. Ancient sulphur cycling and oxygenation of the early biosphere. Elements 6, 93-99.

Marion, G.M., Fritsen, C.H., Hajo, E., Payne, M.C., 2003. The search for life on Europa: Limiting environmental factors, potential habitats, and Earth analogues. Astrobiology 3, 785-811.

Maltagliati, L., Titov, D.V., Encrenaz, T., Melchiorri, R., Forget, F., Garcia-Comas, M., Keller, H.U., Langevin, Y., Bibring, J.-P., 2007. Observations of atmospheric water vapor above the Tharsis volcanoes on Mars with the OMEGA/MEx imaging spectrometer. Icarus, 194, 53–64.

Marzo, G.A., Davila, A.F., Tornabene, L.L., Dohm, J.M., Fairén, A.G., Gross, C., Kneissl, T., Bishop, J.L., Roush, T.L., McKay, C.P., 2010. Evidence for Hesperian impact-induced hydrothermalism on Mars. Icarus 208, 667–683.

McKeown, N.K., Rice, M.S., MacEwan, G., 2011. Detailed mineralogy of Eberswalde crater. 42nd Lunar and Planetary Science Conference, #2450.

McKay, D.S., Gibson, E.K., Thomas-Keptra, K.L., Vali, H., Romanek, C.S., Clemett, S.J., Chiller, X.D.F., Maechling, C.R., Zare, R.N., 1996. Search for past life on Mars: Possible biogenic activity in Martian meteorite ALH84001. Science 273, 924–930.

McKay, D.S., Thomas-Keprta, K.L., Clemett, S.J., Gibson, E.K., Rahmaan, Z., Wentworth, S.J., 2011. Organic carbon features identified in the Nakhla Martian meteorite. 42nd Lunar and Planetary Science Conference, #2673.

McKay, C.P., Porco, C.C., Altheide, T., Davis, W.L., Kral, T.A., 2008. The possible origin and persistence of life on Enceladus and detection of biomarkers in the plume. Astrobiology 8, 909-919.

Melosh, H.J., 1989. Impact Cratering. New York, Oxford University Press.

Mileikowsky, C., Cucinotta, F., Wilson, J.W., Gladman, B., Horneck, G., Lindgren, L., Melosh, H.J,. Rickman, H., Valtonen, M.J., Zheng, J.Q., 2000. Natural transfer of viable microbes in space Part I: From Mars to Earth and Earth to Mars. Icarus 145, 391-427.

Miteva, V., Teacher, C., Sowers, T., Brenchley, J., 2009. Comparison of the microbial diversity at different depths of the GISP2 Greenland ice core in relationship to deposition climates, Environ Microbiol 11, 640–656.

Mittlefehldt D.W., 1994. ALH84001, a cumulate orthopyroxenite member of the Martian meteorite clan. Meteoritics 29, 214–221.

Moore, J.M., Howard, A.D., Dietrich, W.E., Schenk, P.M., 2003. Martian layered fluvial deposits: Implications for Noachian climate scenarios. Geophys Res Lett 30, doi:10.1029/2003GL019002.

Mottl, M.J., Glazer, B.T., Kaiser, R.L., Meech, K.J., 2007. Water and astrobiology. Chemie der Erde-Geochemistry 67, 253-282.

Mustard, J.F., Murchie, S.L., Pelkey, S.M., Ehlmann, B.L., Miliken, R.E., Grant, J.A., Bibring, J.-P., Poulet, F., Bishop, J., Noe Dobrea, E., Roach, L., Seelos, F., Arvidson, R.E., Wiseman, S., Green, R., Hash, C., Humm, D., Malaret, E., McGovern, J.A., Seelos, K., Clancy, T., Clark, R., DesMarais, D.D., Izenbergy, N., Knudson, A., Langevin, Y., Martin, T., McGuire, P., Morris, R., Robinson, M., Roush, T., Smith, M., Swayze, G., Taylor, H., Titus, T., Wolff, M., 2008. Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument. Nature 454, 305-309.

Navarro-Gonzalez, R., Rainey, F.A., Molina, P., Bagaley, D.R., Hollen, B.J., de la Rosa, J., Small, A.M., Quinn, R.C., Grunthaner, F.J., Cáceres, L., Gomez-Silva, B.. McKay, C.P., 2003. Mars-like soils in the Atacama Desert, Chile, and the dry limit of microbial life. Science 302, 1018-1021.

Newsom, H.E., 1980. Hydrothermal alteration on impact melt sheets with implications for Mars. Icarus 44, 207–216.

Newsom, H.E., 2010. Heated lakes on Mars. In: Cabrol, N. and Grin, E. (Eds.), Lakes on Mars. Elsevier, Amsterdam, pp. 91–110.

Newsom, H.E., Brittelle, G.E., Hibbitts, C.A., Crossey, L.J., Kudo, A.M., 1996. Impact crater lakes on Mars. Journ Geophys Res 101, E6, 14951–14955.

Nyquist, L.E., Bansal, B.M., Wiesmann, H., Shih, C.Y., 2001. Ages and geologic histories of Martian meteorites. Space Science Rev 96, 105–64.

Ohba, T., Masaki, M., Ohtsuka, R., 1990. A simulation model for migrations and dispersals of prehistoric human populations. Jinruigaku Zasshi 98, 513-520.

Osbourne, P.E., Alonso, J.C., Bryant, R.G., 2001. Modeling landscape-scale habitat-use using GIS and remote sensing: a case study. Journal Applied Ecology 38, 458-471.

Parkinson, C.D., Liang, M.C., Yung, Y.L., Kirschvink, J.L., 2008. Habitability of Enceladus: Planetary conditions for life. Origin Life Evol Biosph 38, 355-369.

Price, P.B., 2007. Microbial life in glacial ice and implications for a cold origin of life. FEMS Microbiol. Ecol. 59, 217-231.

Rathbun, J.A., Squyres, S.W., 2002. Hydrothermal systems associated with Martian impact craters. Icarus157, 362–372.

Raulin, F., 2007. Why an astrobiological study of Titan will help us understand the origin of life. Origin Life Evol Biosph 37, 345-349.

Raven, J.A., 2009. Contributions of anoxygenic and oxygenic phototrophy and chemolithotrophy to carbon and oxygen fluxes in aquatic environments. Aquatic Microb Ecol 56, 177-192.

Rohde, K., 2005. Nonequilibrium Ecology. Cambridge, Cambridge University Press.

Rushdi, A.I., Simoneit, B.R.T., 2001. Lipid formation by aqueous Fischer-Tropsch-type synthesis over a temperature range of 100-400°C. Origin Life Evol Biosph 31, 103-118.

Russell, M.J., Arndt, N.T., 2005. Geodynamic and metabolic cycles in the Hadean. Biogeosciences 2, 97-111.

Samyn, D., Svensson A., Fitzsimons, S., Lorrain, R., 2005. Ice crystal properties of amber ice and strain enhancement at the base of cold Antarctic glaciers. Annals of Glaciology 40, 185-190.

Schulze-Makuch, D., Dohm, J.M., Fan, C., Fairén, A.G., Rodriguez, J.A.P., Baker, V.R., Fink, W., 2007. Exploration of hydrothermal targets on Mars. Icarus 189, 308–324.

Schwenzer, S.P., 2011. Quantifying low temperature production of methane on Mars. Planetary Science Conference, XLII: #1803.

Schwenzer, S.P., Kring, D.A., 2009. Impact-generated hydrothermal systems: capable of forming phyllosilicates on Noachian Mars. Geology 37, 1091–1094.

Segura, A., Kasting, J.F., Meadows, V., Chen, M., Scalo, J., Crisp, D., Butler, R.A.H., Tinetti, G., 2005. Biosignatures from earth-like planets around M dwarfs. Astrobiology 5, 706-725.

Sephton, M.A., 2002. Organic compounds in carbonaceous meteorites. Nat Prod Rep 19, 292-311.

Skidmore, M., Foght, J., M.J. Sharp, M.J., 2000. Microbial life beneath a High Arctic glacier, Applied Environ Microbiol 66, 3214-3220.

Sleep, N.H., Bird, D.K., 2007. Niches of the pre-photosynthetic biosphere and geologic preservation of Earth's earliest ecology. Geobiology 5, 101-107.

Sleep, N.H., Zahnle, K., 1998. Refugia from asteroid impacts on early Mars and the early Earth. Journ Geophys Res 103, 28529-28544.

Soare, R.J., Osinski, G.R., Roehm, C.L., 2008. Thermokarst lakes and ponds on Mars in the very recent (Late Amazonian) past. Earth Planet Sci Lett 272, 382-393.

Squyres, S.W., Knoll, A.H., 2005. Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars. Earth Planet Sci Lett 240, 1-10.

Stöffler, D., Horneck, G., Ott, S., Hornemann, U., Cockell, C.S., Moeller, R., Meyer, C., de Vera, J.P., Fritz, J., Artemieva, N.A., 2007. Experimental evidence for the potential impact ejection of viable microorganisms from Mars and Mars-like planets. Icarus 186, 585-588.

Stoker, C.R., Zent, A., Catling, D.C., Douglas, S., Marshall, J.R., Archer, D., Clark, B., Kounaves, S.P., Lemmon, M.T., Quinn, R., Renno, N., Smith, P.H., Young, S.M.M., 2010. Habitability of the Phoenix landing site. Journ Geophys Res 115, E00E20.

Swindle, T.D., Treiman, A.H., Lindstrom, D.J., Burkland, M.K., Cohen, B.A., Grier, J., Li, B., Olson, E.K., 2000. Noble gases in iddingsite from the Lafayette meteorite: Evidence of liquid water on Mars in the last few hundred million years. Met Planet Sci 37, 107–115.

Thomas, C.D., Thomas, J.A., Warren, M.S., 1992. Distributions of occupied and vacant butterfly habitats in fragmented landscapes. Oecologia 92, 563-567.

Thomazo, C., Pinti, D., Busigny, V., Ader, M., Hashizume, K., Philippot, P., 2009. Biological activity and the Earth's surface evolution: insights from carbon, sulphur, nitrogen and iron stable isotopes in the rock record. Comptes Rendus Palevol 8, 665-678.

Treiman, A.H., 2005. The nakhlite meteorites: Augite-rich igneous rocks from Mars. Chemie der Erde 65, 203–270.

Turnbull, M.C., 2008. Searching for signs of life in the reflected light from exoplanets – a catalog of nearby target stars. Space Science Rev 135, 335-343.

Turner, G., Knott, S.F., Ash, R.D., Gilmour, J.D., 1997. Ar-Ar Chronology of the Martian meteorite ALH84001: Evidence for the timing of the early bombardment of Mars', Geochim Cosmochim Acta 61, 3835–3850.

Van Berk, W., Ilger, J.-M., Fu, Y., Hansen, C., 2011. Decreasing CO_2 partial pressure triggered Mg–Fe–Ca carbonate formation in ancient Martian crust preserved in the ALH84001 Meteorite. Geofluids 11, 6-17.

Varnes, E.S., Jakorsky, B.M., McCollom, T.M., 2003. Biological potential of Martian hydrothermal systems. Astrobiology 3, 407–414.

Warren-Rhodes, K.A., Rhodes, K.L., Pointing, S.B., Ewing, S.A., Lacap, D.C., Gómez-Silva, B., Amundson, R., Friedmann, E.I., McKay, C.P., 2006. Hypolithic cyanobacteria, dry limit of photosynthesis, and microbial ecology in the hyperarid Atacama Desert. Microbial Ecol 52, 389-398.

Weber, C.F., King, G.M., 2010. Distribution and diversity of carbon monoxide-oxidizing bacteria and bulk bacterial communities across a succession gradient on a Hawaiian volcanic deposit. Environ Microbiol 12, 1855-1867.

Wells, L.E., Armstrong, J.C., Gonzalez, G., 2003. Reseeding of early Earth by impacts of returning ejecta during late heavy bombardment. Icarus 162, 38-46.

Whitman, W.B., Coleman, D.C., Wiebe, W.J., 1998. Prokaryotes: the unseen majority. Proc Natl Acad Sci 95, 6578-6583.

Wierzchos, J., Ascaso, C., McKay, C.P., 2006. Endolithic cyanobacteria in halite rocks from the hyperarid core of the Atacama Desert. Astrobiology 6, 415–422.

Wierzchos, J., Cámara, B., de los Ríos, A., Davila, A.F., Sánchez Almazo, I.M., Artieda, O., Wierzchos, K., Gómez-Silva, B., McKay, C.P., Ascaso, C., 2011. Microbial colonization of Ca-sulfate crusts in the hyperarid core of the Atacama Desert: implications for the search for life on Mars. Geobiology 9, 44-60.

Wilhelms, A., Larter, S.R., Head, I., Farrimond, P., di-Primio, R., Zwach, C., 2001. Biodegradation of oil in uplifted basins prevented by deep-burial sterilization. Nature 411, 1034-1037.

Wolstencroft, R.D., Raven, J.A., 2002. Photosynthesis: likelihood of occurrence and possibility of detection on Earth-like planets. Icarus 157, 535-548.

Zent, A., 2008. A historical search for habitable ice at the Phoenix landing site. Icarus 196, 385-408.

Zolotov, M., Shock, E.L., Niles, P., Leshin, L., 2004. Martian subsurface waters: alkaline and reduced throughout history. Second Conference on Early Mars, Houston, #8036.

Figure legends

Figure 1. A habitability 'triad'. Any planetary environment can be split into one of three categories: 1) uninhabitable, 2) habitable and 3) habitable, but uninhabited. The three types of environment are interchangeable as environmental conditions at a particular location change.

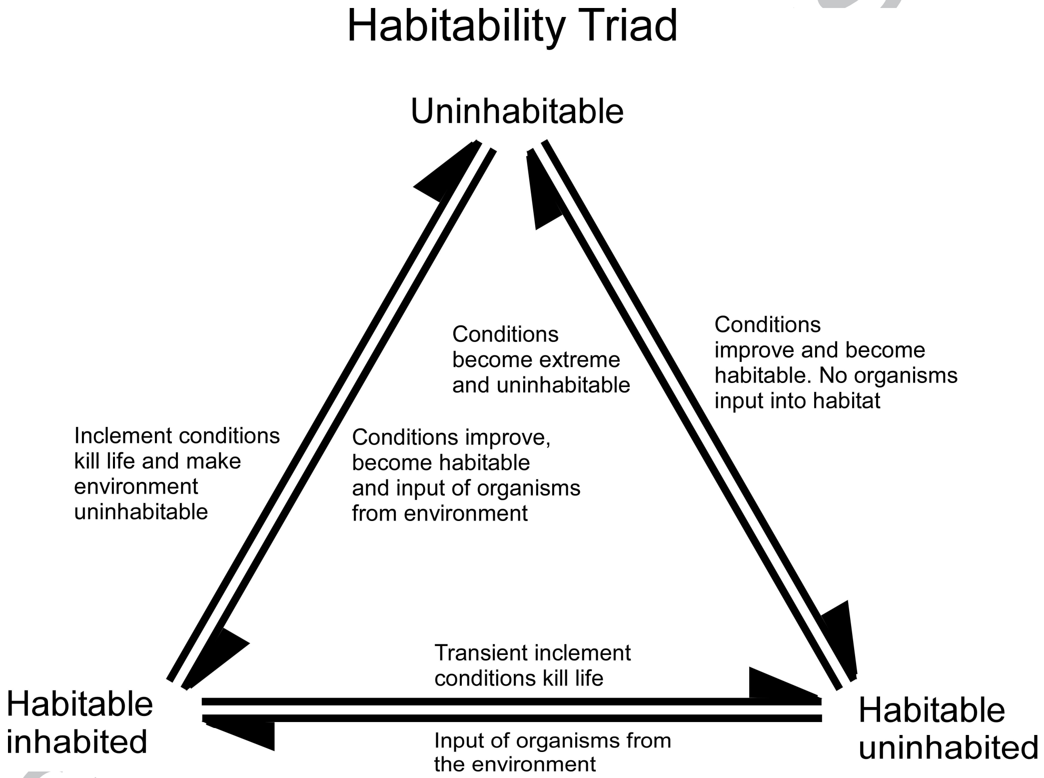


Figure 2. A categorisation of conditions that could lead to uninhabited habitats on Mars. Each numbered scenario is described in the text.

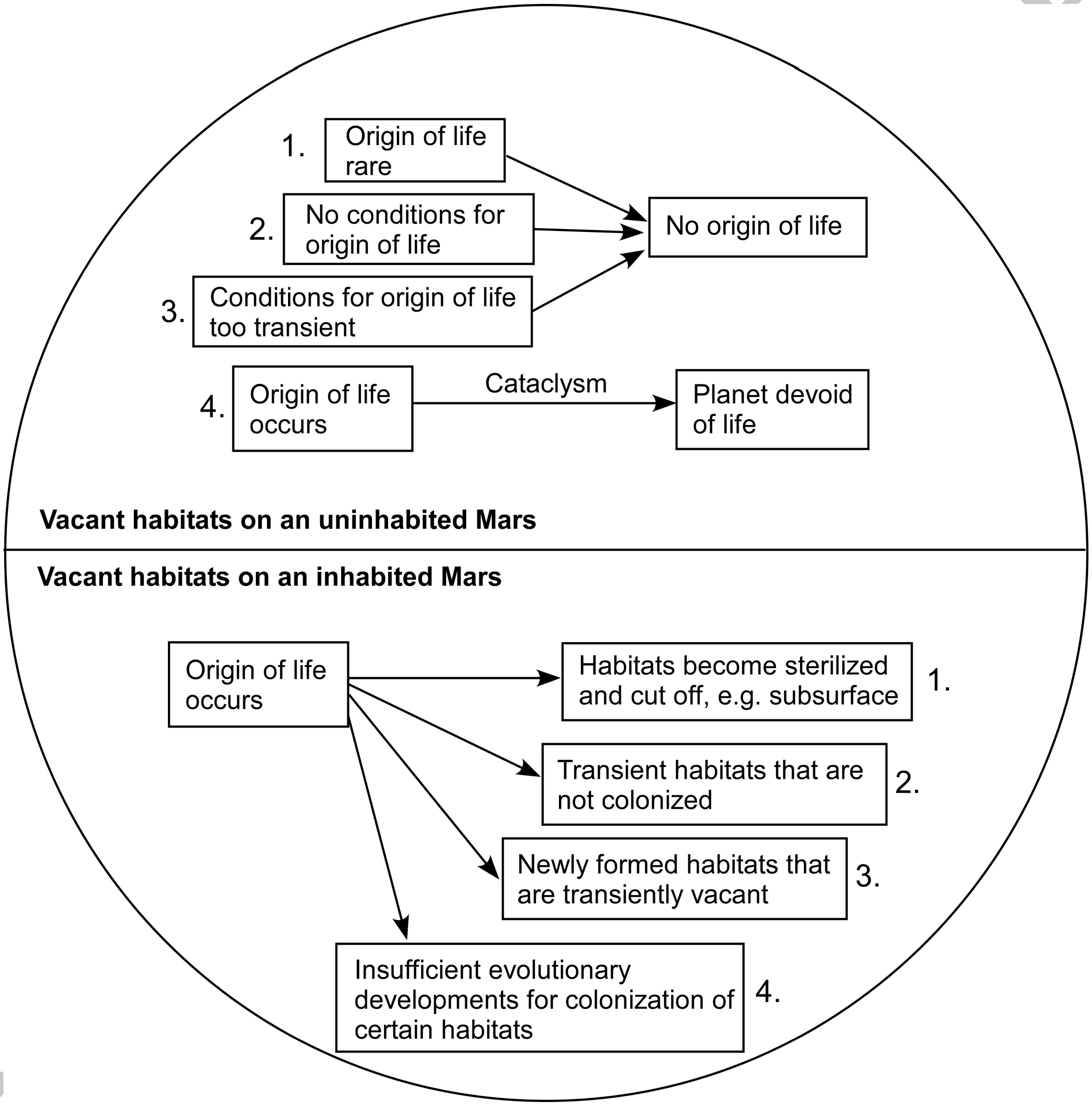
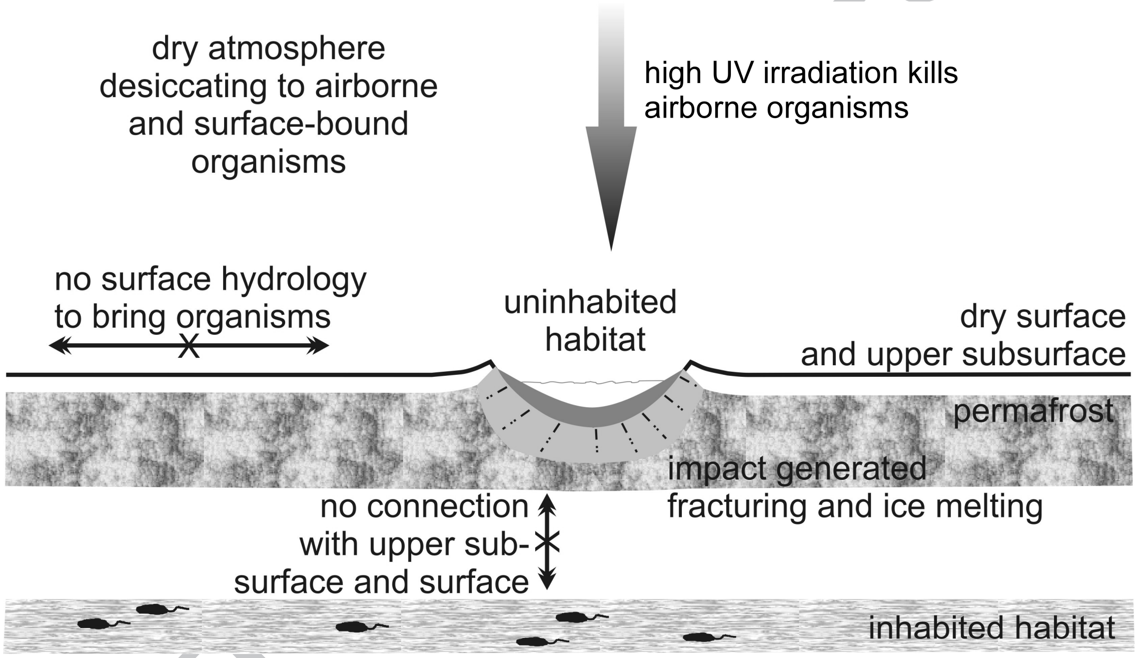


Figure 3. A hypothetical scenario for how an uninhabited habitat could exist on the surface of a planet such as Mars, even if that planet was inhabited in its subsurface. The uninhabited habitat is illustrated in the form of transient melting of permafrost by an impact. However, the scenario is applicable to any habitat that is isolated from inhabited regions or where the rate of transfer of organisms towards the habitat is sufficiently slow to render it uninhabited for significant periods of time.



Highlights:

- First discussion of the possibility that habitats on Mars may be uninhabited.
- Categorisation of uninhabited habitats on Mars and the scenarios by which they might be formed.
- Discussion of how uninhabited might be detected and the possibility that Martian meteorites might provide evidence of them.
- Discussion of the significance of uninhabited habitats to astrobiology and the study of life on the Earth.