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REVIEW ARTICLE

The potential of Deception Island, Antarctica, as a multifunctional Martian analogue of astrobiological interest

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Abstract

The establishment of the possible presence of life on Mars (past or present) is based on the study of planetary analogues, which allow *in situ* analysis of the environments in which living organisms adapt to often extreme conditions. Although Mars has been a candidate for hosting life, based on observations made decades ago, it is thanks to the characteristics identified in environments, mainly volcanic, that it has been possible to calibrate instruments and detail the features of the red planet. In this paper, we present a review of the main characteristics of different planetary analogues, particularly deepening the study of Antarctica, to later expose the factors studied in Deception Island that have contributed to considering it as an analogue of Mars from different perspectives. Although geological and geomorphological studies on the analogies of the island already exist, detailed analyses that present the approach of astrobiological analogues are required, thus allowing further research.

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Introduction

Astrobiology seeks to understand how life emerged and evolved on Earth by relating the physical, chemical and geological characteristics of different environments. It also aims to explore, based on these understandings, the possibilities of life on other rocky bodies in the Solar System or outside it (Des Marais *et al*., 2008; Horneck *et al*., 2016). One of the main goals of astrobiology is to use Earth as a natural laboratory to study the emergence of life and pose models of what life, as we know it, might be like elsewhere in the universe (National Aeronautics and Space Administration (NASA), 2015; Camprubí *et al*., 2019). One of the ways to understand the possible habitability of other planets or satellites corresponds to the evaluation of specific places that present similar conditions to those present in rocky bodies; these places are called planetary analogues, also known as terrestrial analogues (a.k.a. terrestrial analogues) (Fairén *et al*., 2010; Martins *et al*., 2017).

Always taking into account the uniqueness and the noticeable environmental differences that the Earth has in relation to all other rocky bodies of the Solar System, from the perspective of astrobiology, it is possible to classify planetary analogues into two types: (1) field planetary analogues and, (2) laboratory planetary analogues (Martins *et al*., 2017). The first one corresponds to sites distributed on Earth, usually with extreme conditions of pH, temperature, pressure, radiation, salinity and water availability (Amils *et al*., 2007; Bendia *et al*., 2018*a*) in conjunction with some geological or geomorphological features (Martins *et al*., 2017; Matsubara *et al*., 2017). Field planetary analogues enable the development of various types of research, including: (1) understanding geological and geomorphological processes of other bodies, (2) testing and calibrating new instruments, which will be carried aboard space missions, (3) standardizing operational procedures for exploration vehicles and future human crews and (4) collecting biotic and abiotic samples to investigate relationships between life and its geological context, as well as the identification of microorganisms from extreme environments that will allow the evaluation of future methods of detection (or exploitation) of (bacterial) life, instrumentation, payload testing and selection of sites of interest with the potential to harbour life, for future missions (Gómez, 2015; Martins *et al*., 2017; Mouginis-Mark, 2021).

Conversely, laboratory planetary analogues correspond to laboratories used to evaluate parameters of extraterrestrial environments through a series of experiments to understand biological signatures, mechanisms of adaptation and survival of microorganisms and the interaction between life and a simulated atmosphere (Martins *et al*., 2017). In the development of these laboratory analogues, instrument calibration can also be performed (Motamedi Mohammadabadi, 2013). Additionally, it is possible to induce chemical processes or evaluate the behaviour of astro-materials for a broad variety of purposes (Mateo-Martí *et al*., 2006).

Globally, more than 30 analogue sites have been mapped (Martins *et al*., 2017; Cassaro *et al*., 2021; Dypvik *et al*., 2021). Most of them correspond to Mars analogues, and a few others correspond to icy satellites. In astrobiological terms, the search for sites that present extreme conditions for most living organisms has been chosen, aiming to create and evaluate models for the understanding of the adaptation of life to adverse conditions (Cavicchioli *et al*., 2002; Deming, 2009; Garcia *et al*., 2013). Additionally, understanding the different mechanical processes and petrological and mineralogical characteristics are determinants for the geomicrobiological relationships of the various microorganisms and their environment (Henry, 1998; Sajjad *et al*., 2022), a crucial aspect in the search for life elsewhere in the universe.

Within the different extreme environments, a place with low temperatures, strong winds, permafrost and isolation stands out on our planet: Antarctica is considered one of the most suitable analogues for Martian surface processes (Anderson *et al*., 1972). Three locations on the so-called icy continent have been classified as analogue sites (Martins *et al*., 2017). The McMurdo Dry Valleys are considered the driest cold place on the planet (Marchant and Head, 2007), reaching average temperatures of −30°C in winter and −15°C in summer. It has been possible to detect a great richness of microorganisms in the permafrost and rocks (Friedmann, 1982; Gilishinsky *et al*., 2007). It has been considered, since 1975 when Viking missions were launched, to be the closest climatic analogue to Mars conditions (Horowitz *et al*., 1972; Leal *et al*., 2015).

The other two Antarctic analogues are Victoria Land Mountains and Lake Vostok. Victoria Land shares characteristics with McMurdo since dry valleys are also present there, but which, being at a high altitude, promotes the presence of microorganisms resistant even to increased ultraviolet (UV) radiation (Meeßen *et al*., 2015). In case of Lake Vostok, it is one of the places that have been catalogued as an analogue of Enceladus (Saturn's Moon) or Europa (Jupiter's Moon) due to the presence of microorganisms in a lake covered by a layer of ice between 50 and 70 km thick (Shtarkman *et al*., 2013). However, when detailing the geological or petrographic characteristics of these sites, they are considerably distant from being able to be a planetary analogue of any other kind beyond the astrobiological.

Therefore, evaluating other Antarctic sites that may be considered as multifunctional analogues could enhance logistical operations, as well as combine efforts and resources to offer new astrobiological perspectives in the search for life beyond Earth. Among other potential Antarctic multifunctional analogues, Deception Island displays similar characteristics with its counterpart. The reason for selecting this stratovolcano located between the South Shetland Islands and the Antarctic Peninsula (Geyer *et al*., 2019) lies in its geological, geomorphological and climatological, among other characteristics. While this island has been assessed from a geomorphological standpoint (de Pablo *et al*., 2009; Centeno *et al*., 2013; Molina *et al*., 2013, 2014; de Pablo, 2015) and offers logistical facilities that propose it as a possible planetary analogue, allowing the evaluation of sensors for space missions (Ramos *et al*., 2012; de Pablo, 2015), many of its features have yet to be integrated to propose it as a multifunctional analogue of Mars.

For this reason, the present review has the following objectives:

(1) Identify and classify the geological, geomorphological and meteorological characteristics of Deception Island as a multifunctional analogue of Mars.
(2) Describe the astrobiological potential of the island as a Mars analogue.
(3) Identify future research opportunities and further exploration of the island as a Martian analogue.

To address these objectives, the study includes a section that discusses the criteria for the selection of multifunctional analogues, followed by a review of Deception Island's characteristics that may be of interest as an analogue. Subsequently, the island's relevance as an astrobiological Mars analogue is discussed, and finally, there is a discussion on future research perspectives and deeper exploration of the island as a Mars analogue.

Criteria for the selection of multifunctional analogue sites

According to the proposal of Foucher *et al.* (2021), it is possible to classify analogues according to their practical use in planetary exploration. Thus, two major classifications can be found: (1) functional analogue sites and (2) functional analogue samples. Functional analogue sites exhibit general characteristics similar to those found on another extraterrestrial body, but have specific analogous properties of interest for a particular use and are widely used in astronaut training and instrument calibration and contribute to interpreting observations made in space missions. Therefore, analogous sites can be classified according to their function: (1) planetary analogy, (2) analogy of mechanical and chemical processes, (3) petrological and mineralogical analogy, (4) analogy of astrobiological interest and (5) engineering analogy. Analogue samples can be classified into: (1) geological analogue samples, (2) chemical analogue samples, (3) biological samples and (4) technical analogue samples.

Based on the selection pathways of the most appropriate analogue site to be used according to the purpose of the study (Figs. 1 and 2), this study will evaluate Deception Island as a multifunctional analogue that can simultaneously serve as a functional site for two or more categories: engineering, biology, geology, medicine and architecture. However, priority will be given to ensuring that at least one of these corresponds to a scientific study and the other to a technical study.

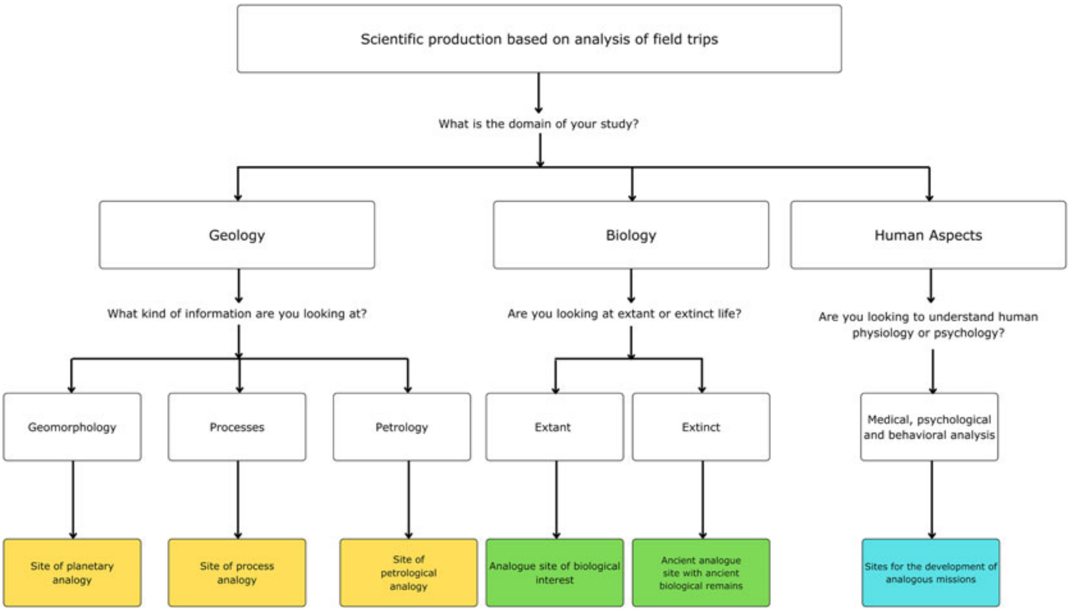

Figure 1. *Aspects to consider for the definition of functional analogue sites of scientific interest. Geological interest sites are marked in yellow, biological interest sites in green and medical interest sites in blue (own construction based on Foucher* et al.*, 2021 and Heinicke and Arnhof, 2021).*

Characteristics of Deception Island with analogous functionality

Geology, geography and geomorphology

Deception Island is located in the South Shetland Islands archipelago, near the Antarctic Peninsula (62° 57′S; 60°38′W). This island is the first planetary analogue proposed in the vicinity of the Antarctic Peninsula, given that some sectors of Antarctica have been considered planetary analogues, such as the Dry Valleys (including the Victoria Mountains and Beacon Valley) and Lake Vostok (Fairén *et al.*, 2010; Martins *et al.*, 2017; Dypvik *et al.*, 2021). However, as shown in Fig. 3, the Antarctic locations classified as analogues are not situated in this region.

Deception Island is one of the three emergent volcanoes in the volcanic complex that developed along the rift axis forming the Bransfield Strait (Caselli *et al.*, 2007). It is a stratovolcano with a caldera collapse that created a central rim with an internal ocean and the characteristic horseshoe shape, as shown in Fig. 4 (Baraldo, 1999). The last eruptive cycle occurred in 1970, after which geothermal anomalies with gas emissions of varying compositions and temperatures were generated (Caselli *et al.*, 1994, 2007; Agusto *et al.*, 2004). The island is a composite volcano, with a basal diameter of 30 km and an elevation of 1400 m from the ocean floor to a maximum of 540 m above sea level (Luzón *et al.*, 2011; Geyer *et al.*, 2019). It is estimated that the island is less than 0.75 million years old (Valencio *et al.*, 1979), and the subaerial part would have formed in the last 0.2 million years (Martí *et al.*, 2013). It is estimated that the caldera collapse released 60 km^2 of magma (Geyer and Marti, 2008), classifying it as a medium-sized caldera, and this process is believed to have occurred between 8300 and 3980 B.C. (Oliva-Urcia *et al.*, 2016).

The magmas on the island range from basaltic to trachydacitic, and the rhyolitic compositions show a characteristic alkaline increase, caused by an unusual rise in sodium oxide. This alkalinity and the incompatible trace element enrichment are consistent with the data recorded in the Bransfield Rift, which also geologically corresponds to the subduction zone where the volcanic arc is formed. On the other hand, it has been identified that the magmas that erupted after the caldera collapse tend to evolve, showing a wide compositional range from basalts to rhyolites (Geyer *et al.*, 2019).

Figure 2. *Aspects to consider for the definition of functional analogue sites of technical interest. Geological interest sites are marked in yellow, biological interest sites in green, engineering interest sites in grey and architectural interest sites in purple (own construction based on Foucher* et al.*, 2021 and Heinicke and Arnhof, 2021).*

The rocks on the island have traditionally been classified as pre- and post-caldera products (González-Ferrán and Katsui, 1970; Baker et al., 1975) and syn-caldera deposits (Geyer *et al.*, 2019). However, later studies allowed for the classification of the rocks into lithologies (Smellie, 1988), and the pre-caldera deposits were divided into two formations: the Basaltic Shield Formation (BSF) and the Yellow Tuff Formation (YTF) (Martí and Baraldo, 1990). The BSF includes basaltic lavas, scoria deposits and palagonitized tuffs. The YTF corresponds to the oldest deposits and consists of palagonitized tuffs with a subsequent effusive lava episode (Martí and Baraldo, 1990; Baraldo, 1999).

On the island, which shows a horseshoe shape, it is possible to distinguish an inner zone and an outer zone mediated by different mountain systems that divide and isolate the exterior from the interior, among which the following stand out: Mount Kirkwood, Mount Irizar, Stonethrow Ridge, Telephone Ridge, Mount Goddard and Mount Pond. Access to the inner zone of the island is through a small opening called Neptune's Bellows. Other notable geographical features of the island include bays with their beaches, such as La Lobera beach, Colatina, Fumarole Bay, Telephone Bay, Pendulum Cove and Whalers Bay. Additionally, in some of these areas, fumaroles have been observed during low tide, as in Fumarole Bay (Fig. 5), Whalers Bay and Pendulum Cove.

On the other hand, due to the intense volcanic activity, lava channels and craters can be distinguished, such as Crater 70 (Fig. 6) and others that have also filled with water, forming crater lakes

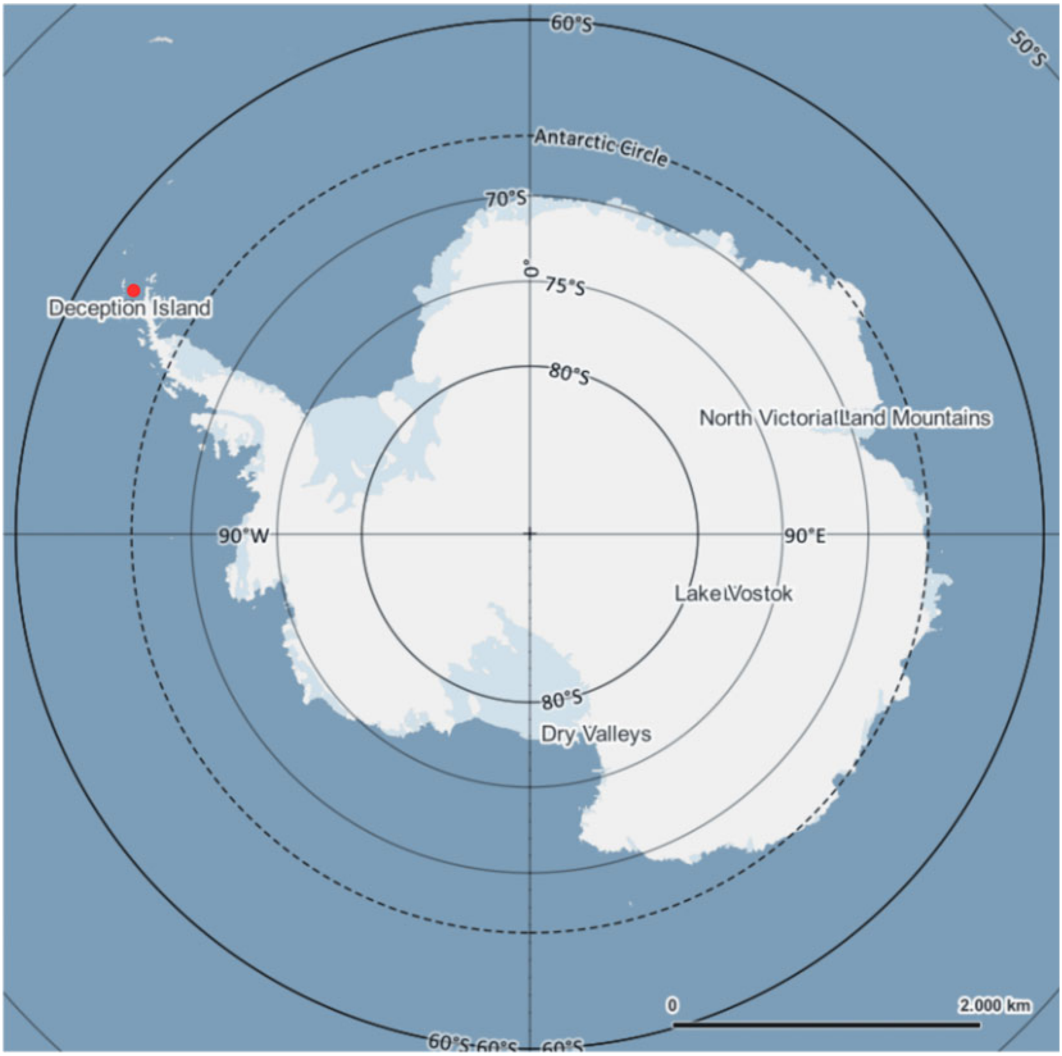

Figure 3. *Location map of the already proposed planetary analogues in Antarctica.* Data source*: Quantarctica v3 (Matsuoka* et al.*, 2018).*

such as Crater Lake, Zapatilla Crater (Fig. 7), Soto Crater, Kroner Lake and Chacao Crater. Another relevant feature is the presence of mountains and hills, such as Cerro Caliente, Mount Irizar, Cerro Crimson, Cerro Ronald and Morro Baily.

The island features numerous glaciers, which significantly alter volcanic structures (Aparicio *et al.*, 1997). One example is the so-called Red Glacier, which consists of weathered rock that contains iron oxides, giving it a reddish colour (Fig. 8). On the other hand, there are glaciers with interlayered strata that reflect ash deposits from past eruptions, resulting in dark coloration on the glacier, which is why it has been named Black Glacier (Fig. 9). Regarding gradational processes, it is possible to identify river and stream patterns, as well as moraines (de Pablo *et al.*, 2009).

Climate and meteorology

Although Deception Island hosted the Argentine Deception Base in 1948 and the Spanish Gabriel de Castilla Base in 1989, records are only available from 2005 onwards. It was from this point that the

Figure 4. *Detail map of Deception Island, the here proposed analogue.* Data source*: Quantarctica v3 (Matsuoka* et al.*, 2018).*

Spanish Meteorological Agency (AEMET) began monitoring the area, following the installation of the meteorological station. Some of the island's most notable features include a historical maximum temperature of 13.3°C in February 2020 and a historical minimum temperature of −22.5°C in July 2007. Regarding atmospheric pressure, the highest recorded pressure was 1025.2 hPa in August 2017, while the lowest was 931.4 hPa, recorded in August 2015. In terms of wind measurements, the highest historical 10 min average was 28.3 $\mathrm{m\,s^{-1}}$, with a maximum gust of 44.6 $\mathrm{m\,s^{-1}}$ (AEMET, 2024).

When analysing the mean atmospheric and soil temperatures for each month, as shown in Fig. 10, it is observed that the months with the lowest temperatures, as expected, correspond to May through August. The ground acts as a buffer against abrupt temperature changes, averaging 0.95°C higher than the atmospheric temperature.

Regarding average wind speed ($\mathrm{m\,s^{-1}}$), according to AEMET (2024), the month with the highest recorded wind speed is August, with a value of 8.2, followed by June with a value of 8.0. In contrast, the months of January and December report the lowest values, 5.4 and 5.7, respectively. Conversely, in

Figure 5. *High-temperature gas emission in Fumarole Bay (photograph taken by David Tovar in December 2022).*

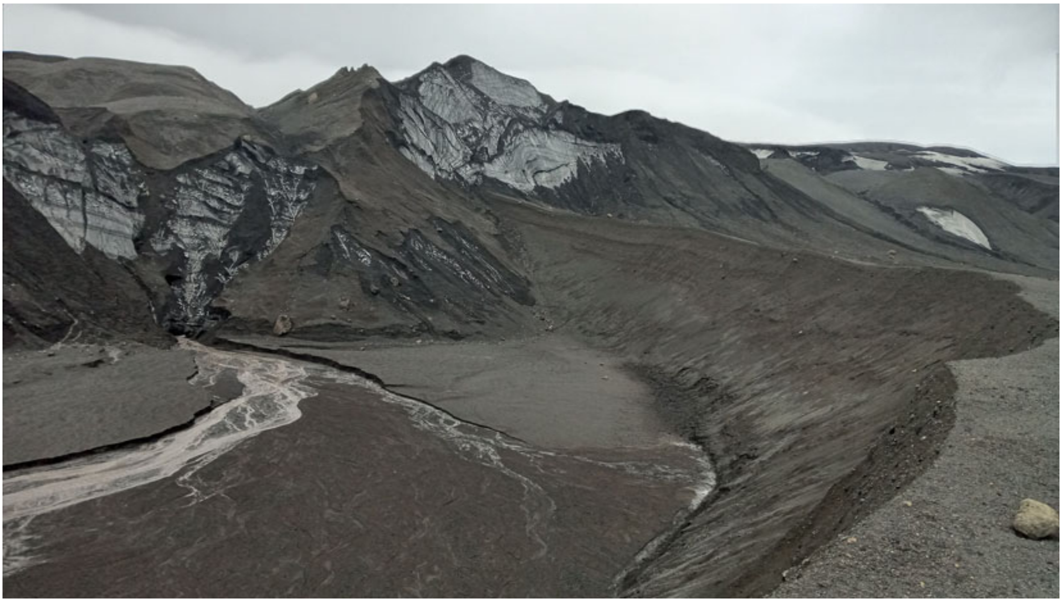

Figure 6. *Area known as Crater 70, where various craters can be observed as a result of volcanic activity from 1970 (photograph taken by David Tovar in December 2022).*

Figure 7. *Zapatilla Crater, which has naturally filled with freshwater through precipitation and runoff processes, creating a crater lake (photograph taken by David Tovar in January 2022).*

Figure 8. *Red glacier, which corresponds to glacial weathering processes of volcanic materials, resulting in the presence of iron oxides that give it its characteristic coloration (photograph taken by David Tovar in January 2023).*

Figure 9. *Black glacier, which features interlayered strata of glacier ice and ash deposits from different eruptive pulses (photograph taken by David Tovar in January 2023).*

terms of average pressure (hPa), the highest reading is observed in September with an average of 998, followed by July with a value of 994 in contrast with, August and October where the lowest measurements are dominant, displaying values of 983 and 989, respectively.

Life on the island

Studies related to the presence of living organisms on Deception Island date back to the 1960s, with studies reporting the presence of spermatophytes and cryptogams (Longton, 1967), as well as the presence of bacteria and yeast (Stanley and Rose, 1967). Of course, numerous studies have been conducted on plant species such as *Colobanthus quitensis* and *Deschampsia antarctica* (Collins, 1969; Greene and Holtom, 1971; Smith, 2005), as well as on animals like *Pygoscelis antarcticus*, since the island hosts three colonies of this penguin (Graña and Montalti, 2012; Masello *et al.*, 2021; Román *et al.*, 2022).

Additionally, Cameron and Benoit (1970) report the presence of microorganisms and their respective relationship with processes associated with microbial ecology in the cinder cones of Deception Island. Studies related to the microbial population present in Antarctica highlight the presence of microorganisms under conditions of desiccation, isolation and aridity, which resemble places in the Solar System such as Mars (Gilishinsky *et al.*, 2007; Gilichinsky *et al.*, 2010; Nicholson *et al.*, 2013).

Some of the microorganisms isolated from the hot soils of Fumarole Bay include *Geobacillus jurassicus*, *Geobacillus thermoleovorans*, *Bacillus fumarioli*, *Bacillus thermantarcticus*, *Brevibacillus thermoruber* and *Thermus* sp., which are thermophilic bacteria that have also been isolated from other geothermal sites in Antarctica (Muñoz *et al.*, 2011). However, not only organisms from high-temperature environments have been studied, but also microorganisms found in the island’s permafrost, demonstrating that both low and high temperatures support microbial growth. Among the representative bacterial phyla found in the permafrost are *Actinobacteria*, *Cyanobacteria*, *Acidobacteria* and *Proteobacteria* (Blanco *et al.*, 2012). Studies conducted on rock samples from the island identified the presence of various endolithic microorganisms, with the predominant genera being *Ralstonia*, *Gaiella* and *Polaromonas* (Hidalgo-Arias *et al.*, 2023).

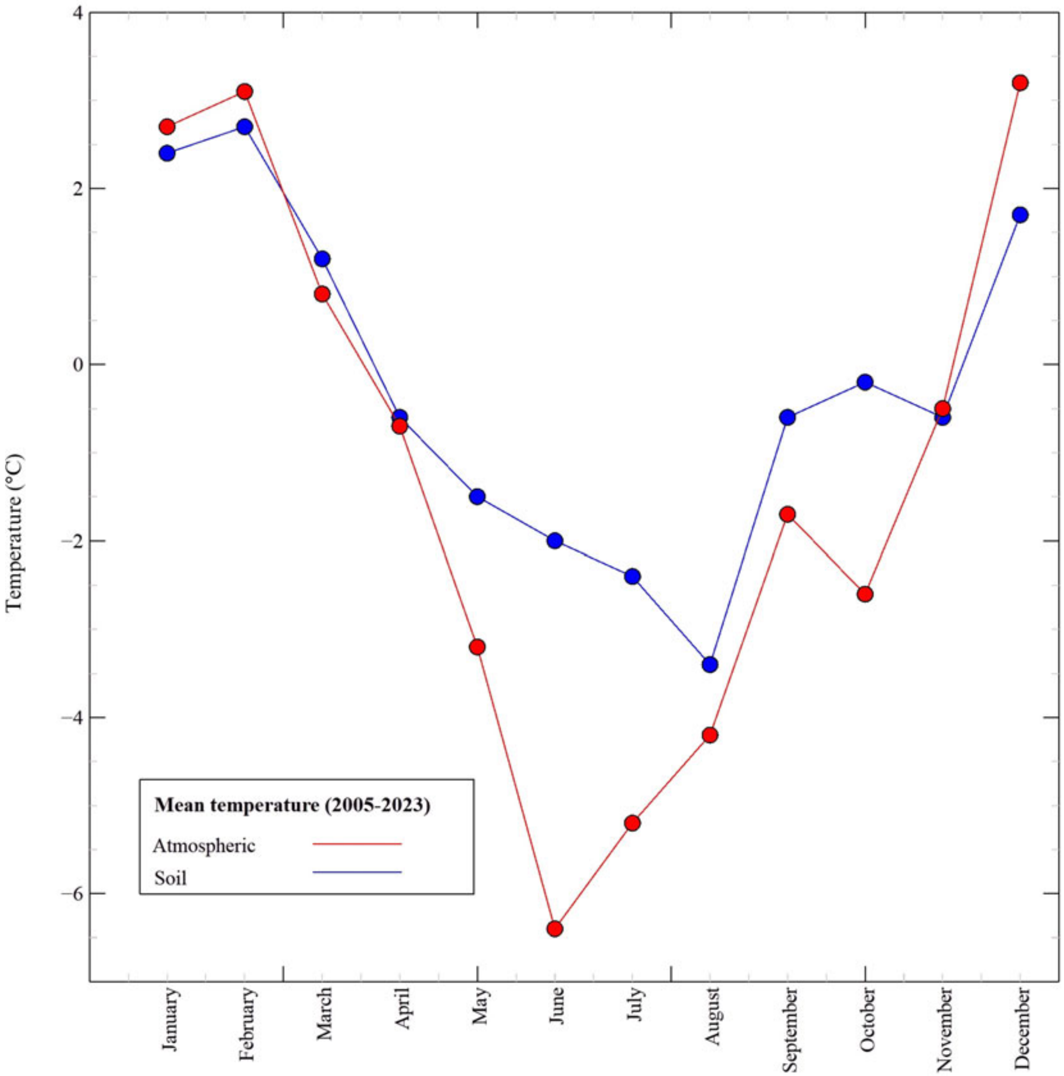

Figure 10. *Mean temperature of Deception Island during the period 2005–2023, recorded at the Spanish Antarctic Base Gabriel de Castilla (*source*: own elaboration based on AEMET data).*

Human life and engineering

Another aspect to consider regarding what can be found on the island includes the operational Antarctic bases, such as the Spanish Antarctic Base Gabriel de Castilla (Fig. 11) and the Argentine Antarctic Base Deception (Fig. 12), as well as the ruins of bases that were eliminated due to volcanic eruptions, such as the British Base and the Chilean Base. The two bases exhibit considerable differences in infrastructure; the Spanish installation features fully modular structures, while the Argentine installation consists of permanent facilities. Another distinguishing aspect relates to the available spaces in the living module, workshops and the presence or absence of a gym, laboratories and medical office.

Regarding engineering for data collection, notable is the evaluation conducted on the island during the 2008–2009 field campaign, where the REMS (Rover Environmental Monitoring Station-Mars Science Laboratory) instrument was tested under the island's conditions. This environmental station was designed by the Centro de Astrobiología (CAB-Spain) in collaboration with national and

Figure 11. *Spanish Temporary Antarctic Station Gabriel de Castilla (photograph taken by Marcos Rozalen of the Spanish Army in January 2023).*

Figure 12. *Argentine Temporary Antarctic Station Decepción (photograph taken by David Tovar in January 2023).*

international partners. The instrument consists of five sensors: soil temperature, air temperature, wind speed and direction, pressure, humidity and UV radiation. One of the most relevant aspects of evaluating it under the island's conditions was the ability to test data collection in the active layer of permafrost and the balance in the boundary layer between soil and atmosphere, which is fundamental for conditions on Mars, where an extensive layer of permafrost exists (Esteban *et al*., 2009; Ramos *et al*., 2012).

Mars

Mars and habitability

Several factors determine the habitability of a planet. From an astrophysical perspective, the star's spectral type around which it orbits is critical. Late G to mid-K type stars are ideal since they have a half-life time that allows life to evolve and emit UV radiation in low proportions concerning O, A and B type stars that will enable some biochemical processes relevant to the emergence of life (Cuntz and Guinan, 2016); moreover, they can host planets at a distance that facilitates the presence of liquid water on the surfaces of the planets orbiting it, in the so-called habitability zone (Kereszturi and Noack, 2016). Other factors include the composition of the planet (rocky planets being those most likely for life to arise), having a sufficient size for gravity to retain an atmosphere, having a maximum orbital eccentricity of ≈0.10 (Dressing *et al*., 2010), axial inclination similar to that of the Earth, presence of a natural satellite as an obliquity stabilizer (Laskar *et al*., 1993), presence of a gas giant that can serve as a protective shield from impacts (Horner and Jones, 2008; Grazier, 2016). Additionally, the company of environmental factors such as the presence of nutrients, water (solid or liquid), energy sources, the existence of elements required for life and various factors recognized as the limits of life must be considered (Beaty *et al*., 2006; Kereszturi and Noack, 2016).

Based on these factors, Mars would be a potential candidate for the search for biofilms in rocky material. In addition to this, unlike other bodies of the inner Solar System, on the red planet, it has been possible to detect traces of clays distributed in some places on the Martian surface. Although they are far from the possible presence of a large-scale ocean on the planet (Leone, 2020, 2021*b*), they could be a source of water and hydrated minerals for some microorganisms. Besides having the presence of basalts containing olivines, pyroxenes and iron oxides (haematite) (Bandfield, 2002; McSween *et al*., 2009; Kasting, 2010), this clay could serve as nutrients for some microorganisms (Hersman *et al*., 1996; Herrera *et al*., 2009; McLoughlin *et al*., 2011) if they can survive cosmic and solar radiation, for example, is the case of organisms such as *Deinococcus radiodurans*, which can tolerate gamma radiation doses of more than 5000 Gy (Daly, 2009; Krisko and Radman, 2013) or *Thermococcus gammatolerans*, which accepts amounts of up to 30 000 Gy (Marín-Tovar *et al*., 2022).

On the other hand, although the red planet has neither active plate tectonics nor a present-day magnetic field, palaeomagnetism records suggest that both plates tectonic processes (Connerney *et al*., 1999; Yin, 2012) and the presence of a global magnetic field (Connerney *et al*., 1999, 2001) could have been present in Mars' past. This first hypothesis must be discarded, considering the lack of subduction zones throughout the planet. The second hypothesis is plausible, considering that a transient magnetic field could have coincided with an epoch of active volcanism between 4550 and 4100 million years ago (Leone *et al*., 2014). But as this intense volcanic activity ended, the magnetic field would have ended (about 4 billion years ago), suggesting that the two processes could have been related to the heat produced by a Giant Impact in the South Pole of the planet (Leone, 2021*b*). This hypothesis was proposed by Reese and Solomatov (2006) and Reese *et al*. (2011), studied with two-dimensional modelling (Golabek *et al*., 2011), refined with three-dimensional (3D) modelling (Leone *et al*., 2014) and validated with the discovery of 12 volcanic alignments that had previously been predicted with 3D modelling (Leone, 2016, 2021*a*).

The hypothesis of volcanic intrusions less than 20 million years old (Mitchell and Wilson, 2003) is not sustainable even with some extreme thermal models of the planet (Leone, 2020, 2021*b*). Although models derived from InSight's seismic data have established the possibility of the presence of currently active magma chambers in the Elysium Planitia region on Mars (Broquet and Andrews-Hanna, 2023). Furthermore, the presence of a thin CO_2 atmosphere (Banfield *et al.*, 2020), an orbital eccentricity of 0.093 (JeongAhn and Malhotra, 2015) and a current obliquity of 25° (Holo *et al.*, 2018), but which has not been stable over time, are not sufficient to ensure large-scale habitability as present on Earth. The lack of water, the distance from the Sun, the currently thin atmosphere, which is not suitable for aerobic organisms and the planet's low gravity that is insufficient to retain this atmosphere are the major factors that distance Mars from Earth in terms of habitability. However, it is necessary to consider that the late Hadean Earth had similar atmospheric conditions and that life was possible (Kasting, 1993; Sleep and Zahnle, 2001; Kasting and Howard, 2006); besides not knowing if, in the past, the atmosphere could have been much thicker.

Regarding ecological factors, it has been possible to find evidence of the apparent presence of liquid water at depth beneath the south-polar region of Mars (Orosei *et al.*, 2018) and ambiguous traces of past water at the surface (Rampe *et al.*, 2020; Moller *et al.*, 2021). This evidence has recently been discussed due to the large amount of olivine on the planet's surface, which could indicate that it is undisturbed after its first eruption 4500 million years ago (Leone, 2020). Although the surface of Mars has the presence of nitrogen, phosphorus, sulphur, calcium, magnesium, chlorine and potassium, considered essential nutrients for life (Kounaves *et al.*, 2014; Bohle *et al.*, 2016; Matsubara *et al.*, 2017; Thomas and Hu, 2019), which while not a total guarantee that life exists either now or in the past, it does facilitate the elements necessary for life. Additionally, perchlorate salts have been identified on its surface (Kounaves *et al.*, 2010), and its soils have been catalogued as gelisols (Certini *et al.*, 2020) that could also be the result of volcanic deposition (Leone, 2020). In terms of temperature, in summer seasons in equatorial zones and at specific times, surface temperatures could exceed 20°C (Joseph *et al.*, 2020*a*, 2020*b*), but extremophile microorganisms could only tolerate the variation in surface temperature throughout the day. All these features make Mars a planet of interest in studies of extremophile habitability in particular protected conditions such as inside lava tubes, under CO_2 ice in the polar caps or artificial sites for space biomining experiments.

However, two hypotheses stand out of the different possibilities for past or present habitability on Mars. From one perspective, the possible presence of endolithic microorganisms, which would have protection from such an adverse environment as the one described, in addition to having different minerals required for their metabolism (Wierzchos *et al.*, 2005; McLoughlin *et al.*, 2011; Meslier and DiRuggiero, 2019; Sajjad *et al.*, 2022). The other possibility lies in the case of microorganisms in the soil, which, even being a few centimetres away, could have developed radiation tolerance mechanisms (Daly, 2009; Krisko and Radman, 2013; Musilova *et al.*, 2015; Marín-Tovar *et al.*, 2022), to low temperatures (D'Amico *et al.*, 2006; Allen *et al.*, 2009; Ayala del Río *et al.*, 2010; Bendia *et al.*, 2018*a*) and nutrient deficit (Parro *et al.*, 2019; Price *et al.*, 2022).

Mars site analogues

Some extreme terrestrial environments can also be considered planetary analogues, given specific geological or climatological characteristics, which resemble some rocky bodies in the Solar System (West *et al.*, 2010*a*, 2010*b*). Of the rocky bodies explored in recent decades, Mars has mainly gained increased relevance in the last decade due to the findings of liquid water reported in the subsurface of the Martian South Pole (Orosei *et al.*, 2018) and in Ultimi Scopuli (Sulcanese *et al.*, 2023), as well as the interest in sending human-crewed missions in the next decade (Levine *et al.*, 2010). The most sceptical scientists could recognize the presence of liquid water in the Martian subsurface, but the depth at which it could be found is more than 1 km, which would generate problems of a practical nature (Leone, 2020). Although a large number of missions sent to the red planet have focused on geochemical, mineralogical, seismic and geothermal studies, it has not yet been possible to return samples from its surface that would allow us to quantitatively establish a detailed and broad mineralogical composition similar to that studied in terrestrial analogues (Rieder *et al.*, 2004; Morrison *et al.*, 2018; Pantazidis *et al.*, 2019). However, some Martian meteorites have been used as a reference for geochemical and mineralogical examination of Martian surface, investigating the chemical composition at the laboratory (Udry *et al.*, 2020).

Nevertheless, there are *in situ* analyses that have allowed us to understand that the soil composition is mainly of volcanic origin (McLennan *et al.*, 2013; Sautter *et al.*, 2013; Ollila *et al.*, 2014; Cousin, 2015), although some analyses have evidenced the presence of rocks of sedimentary origin and aeolian sediments, in places like Gale Crater (Rampe, *et al.*, 2020; Smith *et al.*, 2021; Millan *et al.*, 2022). Given the surface geologic processes identified on Mars, the identification and characterization of sites on Earth that exhibit diverse geologic processes, including those related to past and present volcanic activity as a priority, are critical for the establishment of terrestrial analogues (Byrne, 2019). Other geological processes are of interest in terms of the classification of terrestrial environments as terrestrial analogues; according to Lalla *et al.* (2015), it is necessary to consider three types of processes: (1) those developed by the activity of aeolian, periglacial, evaporitic or alteration processes in arid environments and polar zones, (2) volcanic with snow–ice interaction, effusive eruptions and hydrothermalism and (3) magmatic related to the rock formation. These environments, in conjunction with meteorites recovered on the Earth's surface, are fundamental to understanding the geological processes along the geological evolution of Mars, evaluating the geobiological conditions present to establish possible similes with geological scenarios on the red planet and the different mechanisms to be a habitable place, as well as the calibration of instruments and methodologies that are expected to be implemented in future missions (Pantazidis *et al.*, 2019).

In addition to the above, a feature to be considered when evaluating volcanic environments is the morphometry of the volcanic edifice (Leone *et al.*, 2022) and its eruptive products since endogenous processes usually generate expressions in the crust, while exogenous processes are directly perceived in the surface and the atmosphere (Carr and Head, 2010), conditioning both measurement instruments and the data recorded to obtain information from the relief (Beyer, 2015). It is also essential to understand the evolution of some of the astrophysical conditions to assess habitability on Mars, such as radiation levels, the flux of particles harmful to life coming from the Sun and the rest of the Galaxy, the evolution of the magnetic field, to take them into account in the perspectives of comparison of terrestrial analogues (Kasting *et al.*, 1993; Lammer *et al.*, 2009; Kopparapu *et al.*, 2013; Lorenz, 2019).

Mars site analogue biological interest and analogous mission

Extreme-analogous terrestrial habitats, such as dry, cold environments or environments exposed to an intense flux of UV radiation, have allowed inferring potential oases in which life could inhabit and be sustainable on Mars, as well as their adaptations to these conditions, where the generation of cryptoendolithic communities and structural changes stand out (Horneck, 2008). Habitability can be understood as the capacity of an environment to support the activity of at least one known organism in a given time, also known as instantaneous habitability (Cockell *et al.*, 2016). In addition, it assesses the possibilities of interplanetary human sustainability based on the ability of the species to sustain itself over a long period without depleting its resources (Losch, 2019). In order to achieve the latter condition on Mars, it has been proposed to rely not only on *in situ* and available resources but also on an additional biological module that can be created by microorganisms isolated from terrestrial analogues, such as *Anabaena* spp. (Verseux, *et al.*, 2016).

Thus, within the sustainability capabilities is the evaluation of the viability of microorganisms, defined as the ability of a microbial population to multiply (Guerra and Castro, 2020). Plant capabilities must also be taken into account, this being the measure of the percentage of seeds with the ability to germinate and produce plants under suitable conditions (Pérez *et al.*, 2013), thus offering an opportunity to assess the viability of terrestrial organisms as indicators for habitability and sustainability on Mars. The terrestrial analogues, in turn, allow the realization of analogous missions, advancing and deepening the possible habitability of humans on Mars and which is part of the planetary exploration plans developed by different space agencies around the world (Baum, 2010). As mentioned above, habitability is addressed in these case studies, and sustainability is a branch of habitability (Frank and

Sullivan, 2014), even with technological intervention (Cockell *et al.*, 2016). Some of these sites for the development of analogous missions are Devon Island (Binsted *et al.*, 2010), Mauna Kea (Graham *et al.*, 2015), Dhofar region of Oman (Gruber *et al.*, 2019) and Rio Tinto (Orgel *et al.*, 2014).

One of the most recognized terrestrial analogues in astrobiology is the Atacama Desert in Chile, where the presence of oxidants that inhibit the presence of microorganisms has been reported (Navarro-González *et al.*, 2003; Navarro-González, 2005). According to Navarro-González *et al.* (2003), the soils of the Atacama Desert are characterized by (1) the absence of organic matter in parts per billion, (2) the rapid release of molecular oxygen when soil samples are exposed to water vapour (70–770 nmol g^{-1}) and (3) rapid disappearance of organic matter in some soil samples as if microbial life were present in these samples, which is in direct contradiction with the first result obtained. These results are similar to those obtained by the instruments of the Viking missions once the Martian soil samples were analysed (Soffen, 1977). For future manned missions to Mars, it is necessary to have solutions that will allow future explorers of the red planet to settle and sustain themselves; for this reason, the simulation of Martian soils with terrestrial parent material whose composition is similar to that reported on the Martian surface has become a priority (Certini *et al.*, 2020). These simulated soils are mixed with organic matter to mimic the addition of residual material from previous cultivation (Wamelink *et al.*, 2019).

Rio Tinto in Spain is another terrestrial analogue that has allowed the study of extremophile (acidophilic) microorganisms, which could be present in areas where liquid water existed on the surface or in the subsurface of Mars billions of years ago (Parro *et al.*, 2011). Parro *et al.* (2011) report that using technology capable of detecting biomolecules, it is possible to establish a correlation between factors of high geological and microbiological relevance, such as microenvironments, diagenetic processes and the age of the biomarker profiles present in the analysed samples. These associations can be helpful in defining study areas for future Mars exploration missions.

As mentioned above, Iceland presents some geological similarities to the Martian Noachian period, which is associated with intense volcanic activity and an average amount of water (i.e. 1–2 wt%) naturally contained in the magma that was vapourized and that could have allowed the emergence of life (Clifford, 2001; Villanueva *et al.*, 2015), this if we take into account that aerosol water is usable by microorganisms, and even the same microorganisms, detected in hot springs can behave as aerosols (Ellis *et al.*, 2008; Hurwitz and Lowenstern, 2014). Additionally, studies such as Dragone *et al.* (2023) show that microorganisms can colonize in the early stages of volcanic island formation without needing clear liquid water at the surface. Other examples of analogues, such as the case of the European Mars Analogue for Space Exploration (MASE) project, which sought to evaluate the habitability and detection of life on the red planet, so isolations of various microorganisms were made from the Graenavatn analogue, a low-temperature acidic volcanic lake poor in nutrients, detecting the polyextremotolerant bacterium *Yersinia intermedia*, with the ability to tolerate low pressure, ionizing radiation, variable temperature, osmotic pressure and oxidizing chemical compounds (Schwendner *et al.*, 2016; Gaboyer *et al.*, 2017).

Geological site analogues

Currently, different places on Earth have been classified as planetary analogues (Martins *et al.*, 2017; Foucher *et al.*, 2021) in order to carry out research leading to the study and understanding of the geological evolution of the rocky bodies of the Solar System; such is the case of the volcanic Big Island of Hawaii, which has been catalogued as a terrestrial analogue that resembles some studied areas of the surface of the planet Mars (Tirsch *et al.*, 2012; Nie *et al.*, 2020). Mineralogical studies, including methods such as fluorescence and X-ray diffraction, visible reflectance spectroscopy, near-infrared, Mössbauer and transmission electron microscopy, have been applied to samples of palagonite tephras poor in phyllosilicates on the upper slopes of Mauna Kea volcano, has allowed establishing a geological analogy with some regions of the planet Mars at different latitudes (Morris *et al.*, 2001). Likewise, the dust has been analysed to evaluate magnetic properties for the presence of iron oxides (magnetite) to be compared with the Mars Pathfinder Magnet Array experiment and thus understand the various surface geological processes that have occurred in Martian geological time (Seelos *et al.*, 2010). However, Hawaii has also served as a setting for the development of numerous experiments focused on the calibration and testing of instruments that will go aboard the various Martian rovers (Pommerol *et al.*, 2013; Rumpf *et al.*, 2020); this constitutes another potential of the terrestrial analogues. Mainly alpha particle X-ray spectrometers have been tested, which analyse the concentration of different elements in a broad and diverse range of materials; however, because samples are not prepared beforehand, some interpretation errors may occur, so calibrating them on Earth is essential (Berger *et al.*, 2020). Studies related to the geological evolution of the planet Mars and evidence of future habitability based on terrestrial analogues, particularly the volcanic Island of Hawaii, are currently underway (Hughes *et al.*, 2019). The concerted effort by scientists and engineers to test hypotheses about the surface geological processes that have shaped the red planet, coupled with the need to train astronauts for eventual human-crewed travel, has made this volcanic island a global benchmark as a planetary analogue (Lim *et al.*, 2010; Szocik *et al.*, 2018).

Another recent example of a terrestrial analogue for planetary geology and astrobiology studies is the island of Santorini in Greece (Pantazidis *et al.*, 2019). The classification of basaltic rocks on Santorini is based on three parameters: (1) field relations, (2) petrographic characteristics and (3) chemical characteristics. As mentioned by Marlow *et al.* (2008), most of the knowledge we have about Mars comes from meteorites (Bouvier *et al.*, 2005), astronomical observations with telescopes on Earth (Yen *et al.*, 2005) and space missions including orbiters, *in situ* laboratories and robotic explorers (Squyres *et al.*, 2004; Rampe *et al.*, 2020). The minerals reported on the island of Santorini have some compositional similarities with those found on the surface of Mars, so space agencies such as NASA, with its Planetary Science and Technology Analogue Research (PSTAR) programme, and ESA with the initiative called ESA Exploration Sample Analogue Collection (ESA2C), have this place as a reference for the testing of different Martian exploration missions as well as the collection of rock samples for further studies in planetary geology and astrobiology. As reported by Pantazidis *et al.* (2019), the presence of euhedral olivines and euhedral to subhedral pyroxene phenocrysts immersed in a matrix whose content varies between olivines, pyroxenes and prismatic and skeletal plagioclase crystals. Compositionally these rocks can be compared to those found in the Gusev Crater on Mars (Morris *et al.*, 2004).

The basalts of the Gusev Crater have been classified into four classes characterized by their composition, as explained by Schmidt *et al.* in their study (2013) and Klingelhöfer and his team (2006). These classes are (1) Adirondack, which is characterized as massive angular blocks containing olivine and pyroxene in the Gusev Crater plains (McSween *et al.*, 2004); (2) Backstay, which includes a floating rock (loose, not part of an outcrop) aphyric with microphenocrystic olivine, pyroxene, magnetite and ilmenite, as well as other disaggregated material identified by a Mini-TES (miniature thermal emission spectrometer) at Husband Hill (McSween *et al.*, 2006), (3) the Irvine class, which includes massive to scoriaceous pyroxene- and magnetite-bearing rocks on the flanks of Husband Hill and the inner Columbia Hills basin and (4) the Algonquin class which have lower normative diopside than the Adirondack, Backstay and Irvine classes. The Algonquin class has a more ultramafic composition, and even pristine rocks would have a lower normative diopside (Mittlefehldt *et al.*, 2006). Similarly, their composition is similar to Martian shergottites, characterized by olivine phenocrysts (olivine-phyric texture) (Filiberto, 2017). Martian pyroclastic-ejecta deposits have also been identified within Columbia Hills, namely the layered plateau of Homeplate (Squyres *et al.*, 2007). The rock classes associated with these deposits are alkaline (tephrite) Wishstone (Usui *et al.*, 2008), basaltic glass-rich Clovis (Squyres *et al.*, 2006) and magnetite-rich Barnhill class rocks (Squyres *et al.*, 2007), some of which have evidence of various degrees of aqueous alteration (Squyres *et al.*, 2006; Ming *et al.*, 2008).

These similarities between Santorini Island rocks and Martian rocks offer an excellent opportunity for local scientists, students and teachers who have research projects and need to collect samples for further analysis, as mentioned by Pantazidis *et al.* (2019).

For its part, Iceland and its intense volcanic activity, has served as a study site for understanding processes related to magma–ice interaction, as well as the dynamics of basaltic fissures that allow establishing a comparison with similar volcanic processes in the geological past of Mars (Hughes *et al.*, 2020). For Hughes *et al.* (2020), the detailed study of the effusive-type eruptive styles reported in Iceland provides a preliminary classification that allows an evaluation of geological parameters of volcanic eruptions on Mars and other rocky bodies of the Solar System. In compositional terms, the surface of Mars presents a global distribution of pyroxene-olivine-rich basaltic (Southern Hemisphere/highlands) and possibly volcanic-glass-rich basaltic andesitic (Northern Hemisphere/lowlands) sands resulting from past volcanic action (Ruff and Christensen, 2007). However, the data of the latter composition can be also interpreted as altered/weathered basalt (Wyatt and McSween, 2002; Minitti and Hamilton, 2010; Rogers and Hamilton, 2015). This type of sand is present in Iceland, Hawaii and the Reunion Islands, so their study could contribute to the correct interpretation of the data obtained by remote sensing since the segregation of olivine must be taken into account once the extraction of the spectral composition of sandy lavas on the surface of Mars is done (Mangold *et al.*, 2011). In this type of analysis, the overall lack of water alteration on Mars that terrestrial basalts have must be considered.

The outcrop 'Las Arenas' on the volcanic island of Tenerife, which corresponds to the monogenetic volcanic field of the Canary Islands (Spain), is considered a Martian analogue because of the rocks present there with varied mineralogy that resembles volcanic regions on the surface of Mars (Lalla *et al.*, 2019), even though the alteration processes are different from those that could occur on Mars. Lava flows and associated structures (lava tubes) are processes related to the evolution of the Martian surface that can be studied in the volcanic islands of the Canary Islands. These structures play a fundamental role in planetary geology and astrobiology since, by analysing the morphological parameters, composition and distribution in volcanic fields, it is possible to determine their genesis and evolution in geological time. In addition, they are ideal scenarios for speleology and the study of environmental conditions, ecological and compositional parameters associated with desirable microbial life in the Martian subsurface (Boston *et al.*, 2001; Sauro *et al.*, 2020).

Deception Island as analogue of astrobiological interest

The active volcano of Deception Island, in the South Shetland archipelago of Antarctica, displays a variety of tectonic, volcanic, slope and periglacial landforms similar to those observed on Mars (de Pablo *et al.*, 2009; Molina *et al.*, 2013, 2014). Of particular interest are the glaciers of the island, which are covered by pyroclastic materials from the last eruptions, whose morphologies resemble the potentially covered glaciers described on Mars (de Pablo *et al.*, 2009; de Pablo, 2015). This volcano contains basaltic rocks and andesitic basalts (Martí *et al.*, 1996; Hopfenblatt *et al.*, 2021), which allows for the establishment of another geochemical scenario for evaluating habitable processes. Regarding the geochemical composition of Deception Island rocks, these are similar to Gusev Crater volcanic rock compositions. Pre-caldera (volcanic) and post-caldera (pyroclastic–volcanoclastic) deposits are similar to these compositions, to a comparable degree to that of the Etna volcano and Tenerife Martian analogue terrains, respectively (Fig. 13 and Table 1). This evaluation followed the methodology of figures of merit (FOM) (Rickman *et al.*, 2007, 2009), which has been used for evaluating the geochemical similarity of regolith simulants (e.g. Metzger *et al.*, 2017; Fackrell *et al.*, 2021) and analogue terrain lithologies (e.g. Tovar *et al.*, 2024) to their intended target Martian compositions. FOM values range from 1 (100% similarity) to 0 (completely dissimilar), and values of >0.80 indicate an adequate overlap between the compared compositions (Fackrell *et al.*, 2021).

Guglielmin (2012) stated that hummocky-type terrain on Deception Island has been widely described concerning glacial shrinkage and permafrost aggradation and degradation. However, regarding the assessment of microbiological relationships with a view towards Mars' habitability and sustainability, this field can be further developed on the island.

This type of terrain has been identified on Mars at different latitudes (Mangold, 2005; Machado *et al.*, 2012; Yin *et al.*, 2021), so the interaction between permafrost and the rocks that make up the volcanic edifice of Deception Island should be considered as a fundamental process that can provide

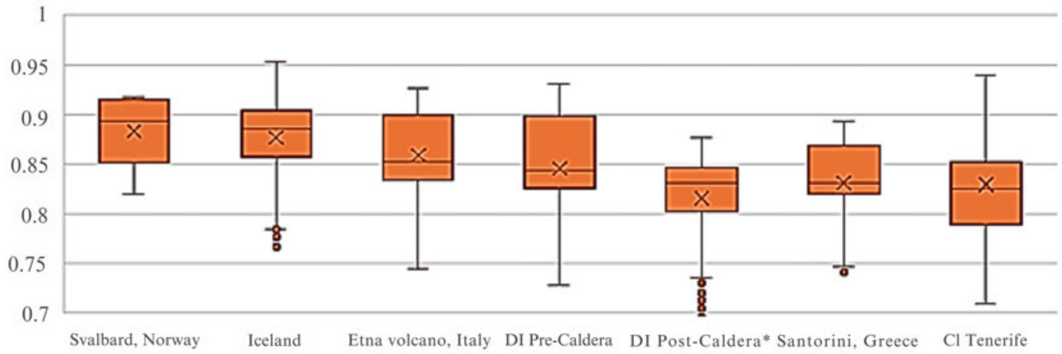

Figure 13. *Boxplot of geochemical FOM values comparison of Gusev Crater compositions, terrestrial analogue sites and Deception Island (DI) Compositions. *Post-caldera pyroclastics were compared with Gusev pyroclastic deposits (Barnhill and Clovis class rocks).*

Table 1. *Average FOM values of the comparison of Gusev Crater and terrestrial analogue terrains' volcanic rock compositions*

	Terrestrial analogues						
				Deception Island			
	Svalbard	Iceland	Etna Volcano	Pre-caldera	Post-caldera[a]	Santorini	Tenerife
Data points	1	44	5	26	154	13	19
Average FOM	0.883	0.877	0.858	0.846	0.816	0.831	0.830

[a] Post-caldera pyroclastics were compared with Gusev pyroclastic deposits (Wishstone, Barnhill and Clovis class rocks). Complete geochemical data is in the Supplementary material (S1).

clues about the geological evolution of Mars and its relationship with certain types of extremophile organisms (Amils *et al*., 2007). Meteorological conditions in this Antarctic volcano are extremely cold, reaching −21°C in winter, with the average temperature in summer exceeding 2°C (Kejna *et al*., 2013). These conditions allow the existence of glaciers on the island despite the volcanic activity evidenced by the presence of fumaroles and areas of geothermal anomalies (Kyle, 1990; Lezcano *et al*., 2019). Characterizing and evaluating Deception Island geologically and geochemically to establish the parameters that would make this place a terrestrial analogue would allow the realization of different research projects on planetary geology, astrobiology and geomicrobiology without having to structure expensive projects whose costs would be unsustainable for the local environment.

In order to contextualize the importance of the Deception Island volcano, it is necessary to understand the processes associated with magma–ice interaction and their relationship with the presence of terrestrial extremophile organisms. Interactions between ice and magma have been a constant in the geological records that constitute the Earth's history (Edwards *et al*., 2015). As Edwards *et al.* (2015) and Head and Wilson (2007) described, volcano–ice interaction is formally termed glaciovolcanism. It can be described as volcanic interaction with all ice forms and associated meltwater. Some locations on planet Earth where the process of glaciovolcanism is widely distributed include Antarctica, Alaska, British Columbia and Iceland (Edwards *et al*., 2015; Curtis and Kyle, 2017).

Glaciovolcanism can create valuable proxies for understanding palaeoclimatic evolution (Edwards *et al*., 2015; Smellie and Edwards, 2016) and acts as a terrestrial analogue for understanding processes associated with some Martian environments (McKenzie and Nimmo, 1999; Ogawa *et al*., 2003; Head and Wilson, 2007). These real-world implications of glaciovolcanism have led to a growing interest in academia about this volcanic process, particularly in studies related to astrobiology (Wierzchos *et al.*, 2005; Cousin, 2015; Edwards *et al.*, 2015). Glaciovolcanism in Antarctica has been recorded as old as 28 Ma (Smellie and Edwards, 2016), making Antarctica the oldest active glaciovolcanic province on Earth. Present-day glaciovolcanism has rarely been recorded in Antarctica due to infrequency and inaccessibility (Wilson and Head, 2002; Smellie and Edwards, 2016). The 1967–1969 Deception Island subglacial eruption is the most studied on the continent (Wilson *et al.*, 2013; Smellie and Edwards, 2016). On the other hand, the interaction of volcanic activity with glaciers, which gives rise to the Black Glacier and Red Glacier, could serve as a model for the search for habitable conditions on Mars, where it has been suggested that survival within the ice could be possible, provided it contains a layer of dust (Khuller *et al.*, 2024).

Prieto-Ballesteros *et al.* (2010) mention geological and biological studies in the region of Crater Lake in Deception Island (Antarctica), whose ultimate goal is to explore the possibility of testing planetary exploration missions on planets like Mars, for which simulations and geophysical studies were conducted in the permafrost in a basaltic plain, in which cores from the borehole were analysed mineralogically and geochemically to detect biological signatures. Lezcano *et al.* (2019), when exploring the Cerro Caliente sector, evaluated how hydrothermal fluids buffered by low atmospheric temperatures allowed the survival of microorganisms, making this a place of interest for understanding possible life on ancient Mars. Hydrothermal zones with microbial mats have also been detected (Fig. 14), are highly relevant in astrobiology research (Vicente *et al.*, 2021).

On the other hand, studies of the presence of perchlorates in Antarctic marine sediments showed that the highest presence of these was recorded on Deception Island, apparently related to a possible volcanic contribution to the formation of perchlorates (Acevedo-Barrios *et al.*, 2022, 2024), which could be related to Martian perchlorates (Kounaves *et al.*, 2014). Another potential of Deception Island is

Figure 14. *Microbial mat related to hydrothermal activity, which is relevant to the understanding of the emergence of life, one of the research areas of astrobiology (photograph taken by David Tovar in December 2022).*

addressed by Blanco *et al*. (2012) by using LDChip300 technology to describe the diversity of natural microbial communities and determine their main operational metabolic pathways present in the Island's permafrost, which colonizes this type of substrate and establishes themselves there.

Bendia *et al*. (2018*a*, 2018*b*) refer to the relationship between Deception Island's geological and environmental conditions, particularly the volcanic activity and the presence of psychrophilic and thermophilic organisms. In these works, Bendia *et al*. (2018*a*, 2018*b*) highlight Deception Island as a terrestrial analogue that studies similar environments on other rocky bodies in the Solar System. Additionally, a great variety of microbial and extremophile mats (thermophiles and psychrophiles) associated with hydrothermal activity resulting from the interaction between magma and surface water in this region in Antarctica have been reported on Deception Island (Lezcano *et al*., 2019). Subsequent studies show a wide diversity of microorganisms present in the volcanoclastic sediments of Deception Island, whose basaltic–andesitic composition is associated with eruptive events typical of the study site (Vicente *et al*., 2021). Finally, in geochemical terms, a notable feature of the island is the basalt-water interaction (Elderfield *et al*., 1977), which could help in understanding the likelihood that Martian rocks were once in contact with water.

Considering the characteristics of Deception Island and the studies carried out in other global analogues, including those located in Antarctica, this volcanic Island offers possibilities for cataloguing as a multifunctional Mars analogue with astrobiological potential (Leal *et al*., 2024), for which it is necessary to increase the spatial resolution of sampling, as well as the geochemical and geomicrobiological evaluation of endolithic and radiophilic organisms, to identify specific regions of Mars with potential for life and similar characteristics to those present on the Island, as well as the study of Antarctic bases as analogous missions.

Conclusions

The characteristics of Mars and the field analogues that can be found on Earth, being candidates for the extreme environments, in particular, sectors of Antarctica that offer opportunities for this type of study so that we can conclude:

(1) Extreme environments for life, such as Deception Island, serve as natural laboratories to understand the development of life and examine the potential for it to have arisen in locations like Mars.
(2) Deception Island, as a volcanic environment, enables *in situ* study of geological, geomicrobiological, climatological and mission-relevant characteristics, providing valuable opportunities to understand rocky bodies within the Solar System.
(3) Deception Island, with its low temperatures and potential for high radiation, desiccation and environmental processes that induce weathering, is ideal for exploring the potential for life on Mars.
(4) Deception Island possesses astrobiological features that make it a potential Mars analogue, including the presence of perchlorates, glaciovolcanic processes, permafrost and evidence of microbial mats able to form under extreme conditions. To confirm its analogy with specific sectors and periods of Mars, a more detailed examination of the island's geochemistry, the presence of endolithic and radiotolerant microorganisms and the development of analogous missions is needed.

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References

Acevedo-Barrios R, Rubiano-Labrador C and Miranda-Castro W (2022) Presence of perchlorate in marine sediments from Antarctica during 2017–2020. *Environmental Monitoring and Assessment* **194**, 1–9.

Acevedo-Barrios R, Puentes Martínez DA, Hernández Rocha IO, Rubiano-Labrador C, De la Parra-Guerra AC, Carranza-López LMonroy-Licht A, Leal MA and Tovar D (2024) Perchlorate in Antarctica, origin, effects, treatments, environmental fate, and astrobiological perspectives: a review. *International Journal of Environmental Science and Technology* **21**, 1–18.

Agencia Estatal de Meteorología (2024) *Informe Antártida 2023*. Madrid, Spain: Agencia Estatal de Meteorología.

Agusto MR, Caselli AT and dos Santos Afonso M (2004) Manifestaciones de piritas framboidales en fumarolas de la Isla Decepción (Antártida): Implicancias genéticas. *Revista de la Asociación Geológica Argentina* **59**, 152–157.

Allen M, Lauro F, Williams T, Burg D, Siddiqui K, De Francisci D, Chong K, Pilak O, Chew H, De Maere M, Ting L, Katrib M, Ng C, Sowers K, Galperin M, Anderson I, Ivanova N, Dalin E, Martinez M, Lapidus A, Hauser L, Land M, Thomas T and Cavicchioli R (2009) The genome sequence of the psychrophilic archaeon, *Methanococcoides burtonii*: the role of genome evolution in cold-adaptation. *The ISME Journal* **3**, 1012–1035.

Amils R, González-Toril E, Fernández-Remolar D, Gómez F, Aguilera Á, Rodríguez N, Malki M, García-Moyano A, Fairén A, de la Fuente V and Sanz JS (2007) Extreme environments as Mars terrestrial analogs: the Rio Tinto case. *Planetary and Space Science* **55**, 370–381.

Anderson D, Gatto L and Ugolii F (1972) An Antarctic analog of Martian permafrost terrain. *Antarctic Journal of the United States* **7**, 114–116.

Aparicio A, Risso C, Viramonte JG, Menegatti N and Petrinovic I (1997) El volcanismo de Isla Decepción (Península Antártida). *Boletin Geológico y Minero* **108**, 235–258.

Ayala del Río H, Chain P, Grzymski J, Ponder M, Ivanova N, Bergholz P, Di Bartolo G, Hauser L, Land M, Bakermans C, Rodrigues D, Klappenbach J, Zarka D, Larimer F, Richardson P, Murray A, Thomashow M and Tiedje J (2010) The genome sequence of *Psychrobacter arcticus* 273–4, a psychroactive Siberian permafrost bacterium, reveals mechanisms for adaptation to low-temperature growth. *Applied and Environmental Microbiology* **76**, 2304–2312.

Baker PE, McReath I, Harvey MR, Roobol MJ and Davies TG (1975) The geology of the South Shetland Islands: V. Volcanic evolution of Deception Island. *British Antarctic Survey* **78**, 1–110.

Bandfield J (2002) Global mineral distribution on Mars. *Journal of Geophysical Research* **107**, 1–20.

Banfield D, Spiga A, Newman C, Forget F, Lemmon M, Lorenz R, Murdoch N, Viudez-Moreiras D, Pla-Garcia J, Garcia RF, Lognonné P, Karatekin Ö, Perrin C, Martire L, Teanby N, Van Hove B, Maki J, Kenda B, Mueller N, Rodriguez S, Kawamura T, McClean J, Stott A, Charalambous C, Millour E, Johnson C, Mittelholz A, Määttänen A, Lewis S, Clinton J, Stähler S, Ceylan S, Giardini D, Warren T, Pike W, Daubar I, Golombek M, Rolland L, Widmer-Schnidrig R, Mimoun D, Beucler É, Jacob A, Lucas A, Baker M, Ansan V, Hurst K, Mora-Sotomayor L, Navarro S, Torres J, Lepinette A, Molina A, Marin-Jimenez M, Gomez-Elvira J, Peinado V, Rodriguez-Manfredi JA, Carcich B, Sackett S, Russell C, Spohn T, Smrekar S and Banerdt WB (2020) The atmosphere of Mars as observed by InSight. *Nature Geoscience* **13**, 190–198.

Baraldo A (1999) *Evolución geológica de la isla Decepción, islas Shetland del Sur, Antártida* (Doctoral dissertation). Buenos Aires, Argentina: Universidad de Buenos Aires. Facultad de Ciencias Exactas y Naturales.

Baum S (2010) Is humanity doomed? Insights from astrobiology. *Sustainability* **2**, 591–603.

Beaty D, Buxbaum K, Meyer M, Barlow N, Boynton W, Clark B, Deming J, Doran PT, Edgett K, Hancock S, Head J, Hecht M, Hipkin V, Kieft T, Mancinelli R, McDonald E, McKay C, Mellon M, Newsom H, Ori G, Paige D, Schuerger AC, Sogin M, Spry JA, Steele A, Tanaka K and Voytek M (2006) Findings of the Mars Special Regions Science Analysis Group. *Astrobiology* **6**, 677–732.

Bendia AG, Araujo GG, Pulschen AA, Contro B, Duarte RT, Rodrigues F and Pellizari VH (2018*a*) Surviving in hot and cold: psychrophiles and thermophiles from Deception Island volcano, Antarctica. *Extremophiles* **22**, 917–929.

Bendia AG, Signori CN, Franco DC, Duarte RT, Bohannan BJ and Pellizari VH (2018*b*) A mosaic of geothermal and marine features shapes microbial community structure on Deception Island Volcano, Antarctica. *Frontiers in Microbiology* **9**, 1–13.

Berger J, Schmidt M, Campbell J, Flannigan E, Gellert R, Ming D and Morris R (2020) Particle induced X-ray emission spectrometry (PIXE) of Hawaiian volcanics: an analogue study to evaluate the APXS field analysis of geologic materials on Mars. *Icarus* **345**, 113708.

Beyer R (2015) An introduction to the data and tools of planetary geomorphology. *Geomorphology* **240**, 137–145.

Binsted K, Kobrick R, Ó Griofa M, Bishop S and Lapierre J (2010) Human factors research as part of a Mars exploration analogue mission on Devon Island. *Planetary and Space Science* **58**, 994–1006.

Blanco Y, Prieto-Ballesteros O, Gómez MJ, Moreno-Paz M, García-Villadangos M, Rodríguez-Manfred JA and Parro V (2012) Prokaryotic communities and operating metabolisms in the surface and the permafrost of Deception Island (Antarctica). *Environmental Microbiology* **14**, 2495–2510.

Bohle S, Perez S, Bille M and Turnbull D (2016) Evolution of soil on Mars. *News and Reviews in Astronomy and Geophysics* **57**, 18–23.

Boston P, Spilde M, Northup D, Melim L, Soroka D, Kleina L and Schelble R (2001) Cave biosignature suites: microbes, minerals, and Mars. *Astrobiology* **1**, 25–55.

Bouvier A, Blichert-Toft J, Vervoot J and Albarède F (2005) The age of SNC meteorites and the antiquity of the Martian surface. *Earth and Planetary Science Letters* **240**, 221–233.

Broquet A and Andrews-Hanna JC (2023) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. *Nature Astronomy* **7**, 160–169.

Byrne P (2019) A comparison of inner Solar System volcanism. *Nature Astronomy* **4**, 321–327.

Cameron RE and Benoit RE (1970) Microbial and ecological investigations of recent cinder cones, Deception Island, Antarctica: a preliminary report. *Ecology* **51**, 802–809.

Camprubí E, de Leeuw J, House C, Raulin F, Russell M, Spang A, Tirumalai MR and Westall F (2019) The emergence of life. *Space Science Reviews* **215**, 1–56.

Carr M and Head J (2010) Geologic history of Mars. *Earth and Planetary Science Letters* **294**, 185–203.

Caselli A, Cohen M and Villegas MT (1994) Geoquímica de gases fumarólicos de la isla Decepción. Su evolución e implicancias volcanológicas. Terceras Jornadas de Comunicaciones sobre Investigaciones Científicas Antárticas, Acta 171–174, Buenos Aires.

Caselli AT, Badi G, Bonatto AL, Bengoa CL, Agusto MR, Bidone A and Ibáñez J (2007) Actividad sísmica y composición química fumarólica anómala debido a posible efecto sello en el sistema volcánico, Isla Decepción (Antártida). *Revista de la Asociación Geológica Argentina* **62**, 545–552.

Cassaro A, Pacelli C, Aureli L, Catanzaro I, Leo P and Onofri S (2021) Antarctica as a reservoir of planetary analogue environments. *Extremophiles* **25**, 1–22.

Cavicchioli R, Siddiqui K, Andrews D and Sowers K (2002) Low temperature extremophiles and their applications. *Current Opinion in Biotechnology* **13**, 253–161.

Centeno JD, de Pablo MA, Molina A and Ramos M (2013) Glaciers on Deception Island, Antarctica: analogue of the debris-covered glaciers on the Hecates Tholus volcano of Mars. In 44th Annual Lunar and Planetary Science Conference. No. 1719, p. 1495.

Certini G, Zhao Y, Meslin P, Cousin A and Hood D (2020) Disambiguating the soils of Mars. *Planetary and Space Science* **186**, 1–13.

Clifford S and Parker T (2001) The evolution of the Martian hydrosphere: implications for the fate of a primordial ocean and the current state of the northern plains. *Icarus* **154**, 40–79.

Cockell C, Bush T, Bryce C, Direito S, Fox M, Harrison J, Lammer H, Landenmark H, Martin-Torres J, Nicholson N, Noack L, O'Malley-James J, Payler SJ, Rushby A, Samuels T, Schwendner P, Wadsworth J and Zorzano MP (2016) Habitability: a review. *Astrobiology* **16**, 1–29.

Collins NJ (1969) The effects of volcanic activity on the vegetation of Deception Island. *British Antarctic Survey Bulletin* **21**, 79–94.

Connerney J, Acuña M, Wasilewski P, Ness N, Rème H, ,Mazelle CVignes D, Lin RP, Mitchell DL and Cloutier PA (1999) Magnetic lineations in the ancient crust of Mars. *Science* **284**, 794–798.

Connerney J, Acuña M, Wasilewski P and Kletetschka G (2001) The global magnetic field on Mars and implications for crustal evolution. *Geophysical Research Letters* **28**, 4015–4018.

Cousins C (2015) Volcanogenic fluvial-lacustrine environments in Iceland and their utility for identifying past habitability on Mars. *Life* **5**, 568–586.

Cuntz M and Guinan F (2016) About exobiology: the case for Dwarf K stars. *The Astrophysical Journal* **827**, 1–9.

Curtis A and Kyle P (2017) Methods for mapping and monitoring global glaciovolcanism. *Journal of Volcanology and Geothermal Research* **333-334**, 134–144.

Daly M (2009) A new perspective on radiation resistance based on *Deinococcus radiodurans*. *Nature Reviews Microbiology* **7**, 237–245.

D'Amico S, Collins T, Marx J, Feller G and Gerday C (2006) Psychrophilic microorganisms: challenges for life. *EMBO Reports* **7**, 385–389.

de Pablo M (2015) *Geomorfología glaciar del flanco noreste del volcán Hecates Tholus, Marte*. Madrid: Universidad Complutense de Madrid.

de Pablo M, Ramos M, Vieira G, Gilichinsky D, Gómez F, Molina A and Segovia R (2009) Deception Island, Antarctica: a terrestrial analogue for the study and understanding of the Martian permafrost and subsurface glaciers. EGU General Assembly 2008 (p. 1292).

Deming J (2009) Extremophiles: cold environments. In Schaechter M (ed.), *Encyclopedia of Microbiology.* San Diego, CA: Estados Unidos: Associated Press, p. 3945.

Des Marais D, Nuth J, Allamandola L, Boss A, Farmer J, Hoehler T, Jakosky BM, Meadows VS, Pohorille A, Runnegar B and Spormann A (2008) The NASA astrobiology roadmap. *Astrobiology* **8**, 715–730.

Dragone N, Whittaker K, Lord O, Burke E, Dufel H, Hite E, Miller F, Page G, Slayback D and Fierer N (2023) The early microbial colonizers of a short-lived volcanic island in the Kingdom of Tonga. *mBio* **14**, 1–15.

Dressing C, Spiegel D, Scharf C, Menou K and Raymond S (2010) Habitable climates: the influence of eccentricity. *The Astrophysical Journal* **721**, 1295–1307.

Dypvik H, Hellevang H, Krzesińska A, Sætre C, Viennet JC, Bultel B, Ray D, Poulet F, Loizeau D, Veneranda M, Rull F, Cousin A and Werner SC (2021) The Planetary Terrestrial Analogues Library (PTAL) – an exclusive lithological selection of possible Martian earth analogues. *Planetary and Space Science* **208**, 105339.

Edwards BR, Gudmundsson MT and Russell JK (2015) Glaciovolcanism. In Sigurdsson H (ed.), *Encyclopedia of Volcanoes*. Londres: Academic Press, pp. 377–393.

Elderfield H, Gunnlaugsson E, Wakefield SJ and Williams PT (1977) The geochemistry of basalt–sea–water interactions: evidence from Deception Island, Antarctica, and Reykjanes, Iceland. *Mineralogical Magazine* **41**, 217–226.

Ellis D, Bizzoco R and Kelley S (2008) Halophilic Archaea determined from geothermal steam vent aerosols. *Environmental Microbiology* **10**, 1582–1590.

Esteban B, Ramos M, Sebastián E, Armiens C, Gómez-Elvira J, Cabos W and De Pablo MA (2009) The Antarctic permafrost as a testbed for REMS (Rover Environmental Monitoring Station – Mars Science Laboratory). Proceedings of EGU General Assembly.

Fackrell LE, Schroeder PA, Thompson A, Stockstill-Cahill K and Hibbitts CA (2021) Development of Martian regolith and bedrock simulants: potential and limitations of Martian regolith as an in-situ resource. *Icarus* **354**, 114055.

Fairén A, Davila A, Lim D, Bramall N, Bonaccorsi R, Zavaleta J, Uceda E, Stoker C, Wierzchos J, Dohm J, Amils R, Andersen D and McKay C (2010) Astrobiology through the ages of Mars: the study of terrestrial analogues to understand the habitability of Mars. *Astrobiology* **10**, 821–843.

Filiberto J (2017) Geochemistry of Martian basalts with constraints on magma genesis. *Chemical Geology* **466**, 1–14.

Foucher F, Hickman-Lewis K, Hutzler A, Joy KH, Folco L, Bridges JC, Wozniakiewicz P, Martínez-Frías J, Debaille V, Zolensky M, Yano H, Bost N, Ferrière L, Lee M, Michalski J, Schroeven-Deceuninck H, Kminek G, Viso M, Russell S, Smith C, Zipfel J and Westall F (2021) Definition and use of functional analogues in planetary exploration. *Planetary and Space Science* **197**, 105162.

Frank A and Sullivan W (2014) Sustainability and the astrobiological perspective: framing human futures in a planetary context. *Anthropocene* **5**, 32–41.

Friedmann EI (1982) Endolithic microorganisms in the Antarctic cold desert. *Science* **215**, 1045–1053.

Gaboyer F, Le Milbeau C, Bohmeier M, Schwendner P, Vannier P, Beblo-Vranesevic K, Rabbow E, Foucher F, Gautret P, Guégan R, Richard A, Sauldubois A, Richmann P, Perras AK, Moissl-Eichinger C, Cockell CS, Rettberg P, Marteinsson, Monaghan E, Ehrenfreund P, Garcia-Descalzo L, Gomez F, Malki M, Amils R, Cabezas P, Walter N and Westall F (2017) Mineralization and preservation of an extremotolerant bacterium isolated from an early Mars analog environment. *Scientific Reports* **7**, 1–14.

Garcia L, Alcazar A and Baquero F (2013) Biotechnological applications of cold-adapted bacteria. In Singh O (ed.), *Extremophiles: Sustainable Resources and Biotechnologgical Implications*. NJ: Wiley-Blackwell, pp. 159–174.

Geyer A and Marti J (2008) The new worldwide collapse caldera database (CCDB): a tool for studying and understanding caldera processes. *Journal of Volcanology and Geothermal Research* **175**, 334–354.

Geyer A, Álvarez-Valero AM, Gisbert G, Aulinas M, Hernández-Barreña D, Lobo A and Martí J (2019) Deciphering the evolution of Deception Island's magmatic system. *Scientific Reports* **9**, 373.

Gilichinsky D, Rivkina E, Vishnivetskaya T, Gomez F, Mironov V, Blamey J, Ramos M, de Pablo MA, Castro M and Boehmwald F (2010) Habitability of Mars: hyperthermophiles in permafrost. 38th COSPAR Scientific Assembly (p. F34).

Gilishinsky DA, Wilson GS, Friedmann EI, McKay CP, Sletten RS, Rivkina EM, Vishnivetskaya TA, Erokhina LG, Ivanushkina NE, Kochkina GA, Shcherbakova VA, Soina VS, Spirina EV, Vorobyova EA, Fyodorov-Davydov DG, Hallet B, Ozerskaya SM, Sorokovikov VA, Laurinavichyus KS, Shatilovich AV, Chanton JP, Ostroumov VE and Tiedje JM (2007) Microbial populations in Antarctic permafrost: biodiversity, state, age, and implication for astrobiology. *Astrobiology* **7**, 275–311.

Golabek GJ, Keller T, Gerya TV, Zhu G, Tackley PJ and Connolly JA (2011) Origin of the Martian dichotomy and Tharsis from a giant impact causing massive magmatism. *Icarus* **215**, 346–357.

Gómez F (2015) Terrestrial analog. In Gargaud M, William M, Amils R, Henderson J, Daniele L, Cernicharo J and Michel V (eds), *Encyclopedia of Astrobiology*. Berlin: Springer-Verlag, p. 2810.

González-Ferrán O and Katsui Y (1971) *Estudio Integral del Volcanismo Cenozoico Superior: De Las Islas Shetland Del Sur, Antártica*. Instituto Geográfico Militar: Universidad de Chile. Santiago de Chile, Chile.

Graham L, Graff T, Yingst A, Kate I and Russell P (2015) 2012 Moon Mars analog mission activities on Mauna Kea, Hawai'i. *Advances in Space Research* **55**, 2405–2413.

Graña Grilli M and Montalti D (2012) Trophic interactions between brown and south polar skuas at Deception Island, Antarctica. *Polar Biology* **35**, 299–304.

Grazier K (2016) Jupiter: cosmic Jekyll and Hyde. *Astrobiology* **16**, 23–38.

Greene DM and Holtom ANNE (1971) Studies in *Colobanthus quitensis* (Kunth) Bartl. a *Deschampsia antarctica* Desv.: III. Distribution, habitats and performance in the Antarctic botanical zone. *British Antarctic Survey Bulletin* **26**, 1–29.

Gruber S, Grömer G and Haider O (2019) Inspiring the next generation through the AMADEE-18 MARS analog simulation. *Acta Astronautica* **164**, 204–211.

Guerra M and Castro J (2020) Evaluación de viabilidad de microorganismos. In Castro J (ed.), *Conformación de colecciones de cultivos microbianos*. Santiago de Chile: Instituto de Investigaciones Agropecuarias INIA-Ministerio de Agricultura, pp. 139–153.

Guglielmin M (2012) Advances in permafrost and periglacial research in Antarctica: a review. *Geomorphology* **155**, 1–6.

Head JW and Wilson L (2007) Heat transfer in volcano–ice interactions on Mars: synthesis of environments and implications for processes and landforms. *Annals of Glaciology* **45**, 1–13.

Heinicke C and Arnhof M (2021) A review of existing analog habitats and lessons for future lunar and Martian habitats. *REACH* **21**, 100038.

Henry E (1998) Geomicrobiology: its significance for geology. *Earth-Science Reviews* **45**, 45–60.

Herrera A, Cockell CS, Self S, Blaxter M, Reitner J, Thorsteinsson T and Tindle A (2009) A cryptoendolithic community in volcanic glass. *Astrobiology* **9**, 369–381.

Hersman L, Maurice P and Sposito G (1996) Iron acquisition from hydrous Fe(III)-oxides by an aerobic *Pseudomonas* sp. *Chemical Geology* **132**, 25–31.

Hidalgo-Arias A, Muñoz-Hisado V, Valles P, Geyer A, Garcia-Lopez E and Cid C (2023) Adaptation of the endolithic biome in Antarctic volcanic rocks. *International Journal of Molecular Sciences* **24**, 13824.

Holo S, Kite E and Robbins S (2018) Mars obliquity history constrained by elliptic crater orientations. *Earth and Planetary Science Letters* **496**, 206–214.

Hopfenblatt J, Geyer A, Aulinas M, Álvarez-Valero A, Gisbert G, Kereszturi G and Angulo C (2021) Formation of Stanley Patch volcanic cone: new insights into the evolution of Deception Island caldera (Antarctica). *Journal of Volcanology and Geothermal Research* **415**, 107249.

Horneck G (2008) The microbial case for Mars and its implication for human expeditions to Mars. *Acta Astronautica* **63**, 1015–1024.

Horneck G, Walter N, Westall F, Lee J, Martin W, Gomez F, Leuko S, Lee N, Onofri S, Tsiganis K, Saladino R, Pilat-Lohinger E, Palomba E, Harrison J, Rull F, Muller C, Strazzulla G, Brucato J, Rettberg P and Capria MT (2016) Astromap European astrobiology roadmap. *Astrobiology* **16**, 201–243.

Horner J and Jones B (2008) Jupiter: friend or foe? *Astronomy and Geophysics* **49**, 22–27.

Horowitz NH, Hubbard JS and Hobby GL (1972) The carbon-assimilation experiment: the Viking Mars Lander. *Icarus* **16**, 147–152.

Hughes S, Haberle C, Nawotniak S, Sehlke A, Garry W, Elphic R and Lim D (2019) Basaltic terrains in Idaho and Hawaii as planetary analogues for Mars geology and astrobiology. *Astrobiology* **19**, 1–24.

Hughes S, Garry W, Sehlke A, Christiansen E, Nawotniak S, Sears D, Elphic R, Lim D and Heldmann J (2020) Basaltic fissure types on Earth: suitable analogs to evaluate the origins of volcanic terrains on the Moon and Mars? *Planetary and Space Science* **193**, 105091.

Hurwitz S and Lowenstern J (2014) Dynamics of the Yellowstone hydrothermal system. *Reviews of Geophysics* **52**, 375–411.

JeongAhn Y and Malhotra R (2015) The current impact flux on Mars and its seasonal variation. *Icarus* **262**, 140–153.

Joseph R, Duxbury N, Kidron G, Gibson C and Schild R (2020*a*) Mars: life, subglacial oceans, abiogenic photosynthesis, seasonal increases and replenishment of atmospheric oxygen. *Open Astronomy* **29**, 189–209.

Joseph R, Gibson C and Schild R (2020*b*) Water, ice, mud in the Gale Crater: implications for life on Mars. *Journal of Cosmology* **29**, 1–33.

Kasting J (1993) Earth's early atmosphere. *Science* **259**, 920–926.

Kasting J (2010) *How to Find a Habitable Planet*. NJ: Princeton University Press.

Kasting J and Howard M (2006) Atmospheric composition and climate on the early Earth. *Philosophical Transactions of the Royal Society B* **361**, 1733–1742.

Kasting J, Whitmire D and Reynolds R (1993) Habitable zones around main sequence stars. *Icarus* **101**, 108–128.

Kejna M, Arazny A and Sobota I (2013) Climatic change on King George Island in the years 1948–2011. *Polish Polar Research* **34**, 213–235.

Kereszturi A and Noack L (2016) Review on the role of planetary factors on habitability. *Origins of Life and Evolution of Biospheres* **46**, 473–486.

Khuller AR, Warren SG, Christensen PR and Clow GD (2024) Potential for photosynthesis on Mars within snow and ice. *Communications Earth & Environment* **5**, 583.

Klingelhöfer G, Morris R, Yen A, Ming D, Schröder C and Rodionov D (2006) Mineralogy on Mars at Gusev Crater and Meridiani Planum as seen by iron Mössbauer spectroscopy. *Geochimica et Cosmochimica Acta Supplement* **70**, A325.

Kopparapu R, Ramírez R, Kasting J, Eymet V, Robinson T, Mahadevan S and Deshpande R (2013) Habitable zones around main-sequence stars: new estimates. *The Astrophysical Journal* **765**, 1–19.

Kounaves S, Hecht M, Kapit J, Quinn R, Catling D, Clarck B, Ming D, Gospodinova K, Hredzak P, McElhoney K and Shusterman J (2010) Soluble sulfate in the Martian soil at the Phoenix landing site. *Geophysical Research Letters* **37**, 1–5.

Kounaves S, Chaniotakis N, Chevrier V, Carrier B, Folds K, Hansen V, McElhoney KM, O'Neil GD and Weber AW (2014) Identification of the perchlorate parent salts at the Phoenix Mars landing site and possible implications. *Icarus* **232**, 226–231.

Krisko A and Radman M (2013) Biology of extreme radiation resistance: the way of *Deinococcus radiodurans*. *Cold Spring Harbor Perspectives in Biology* **5**, 1–13.

Kyle P (1990) Geothermal resources of Antarctica. *Antarctic Resolution* **51**, 117–123.

Lalla EA, López-Reyes G, Sansano A, Sanz-Arranz A, Schmanke D, Klingelhöfer G, Medina-García J, Martínez-Frías J and Rull-Pérez F (2015) Estudio espectroscópico y DRX de afloramientos terrestres volcánicos en la isla de Tenerife como posibles análogos de la geología marciana. *Estudios Geológicos* **71**, e035.

Lalla E, López-Reyes G, Lozano-Gorrín A and Rull F (2019) Combined vibrational, structural, elemental and Mössbauer spectroscopic analysis of natural phillipsite (zeolite) from historical eruptions in Tenerife, Canary Islands: implication for Mars. *Vibrational Spectroscopy* **101**, 10–19.

Lammer H, Bredehöft J and Coustenis A (2009) What makes a planet habitable? *Astronomy and Astrophysics Review* **17**, 181–249.

Laskar J, Joutel F and Robutel P (1993) Stabilization of the Earth's obliquity by the Moon. *Nature* **361**, 615–617.

Leal M, Escobar J, Amaris A, Saavedra F, Tovar D, Delgado C, Reyes R, Barriga O, Doresty F, Pinilla M, Castañeda Y, Pérez C, Mantilla F, Ojeda O and Álvarez N (2015) *Temas selectos en Astrobiología*. Bogotá: Universidad Nacional de Colombia.

Leal MA, Tovar D, de Pablo MA, Bonilla MA, Leone G, Tchegliakova N, Sánchez J, Molina A and San Martín J (2024) The potential of Deception Island (Antarctica) as a Martian analogue of astrobiological interest. *LPI Contributions* **3040**, 1544.

Leone G (2016) Alignments of volcanic features in the southern hemisphere of Mars produced by migrating mantle plumes. *Journal of Volcanology and Geothermal Research* **309**, 78–95.

Leone G (2020) The absence of an ocean and the fate of water all over the Martian history. *Earth and Space Science* **7**, 1–16.

Leone G (2021*a*) History of scientific studies and current views of Mars. In Leone G (ed.), *Mars: A Volcanic World*. Berlin: Springer, pp. 1–17.

Leone G (2021*b*) The formation of Mars and the origin of its volcanic provinces. In Leone G (ed.), *Mars: A Volcanic World*. Berlin: Springer, pp. 19–50.

Leone G, Tackley P, Gerya T, May D and Zhu G (2014) Three-dimensional simulations of the southern polar giant impact hypothesis for the origin of the Martian dichotomy. *Geophysical Research Letters* **41**, 8736–8743.

Leone G, Grosse P, Ahrens C and Gasparri D (2022) Geomorphological and morphometric characteristics of the volcanic edifices along a volcanic alignment of Tharsis on Mars. *Geomorphology* **414**, 108385.

Levine J, Garvin J and Beaty D (2010) Humans on Mars: why Mars? Why humans? Planning for the scientific exploration of Mars by humans part 1. *Journal of Cosmology* **12**, 3627–3635.

Lezcano M, Moreno-Paz M, Carrizo D, Prieto-Ballesteros O, Fernández-Martínez M, Sánchez-García L and Parro V (2019) Biomarker profiling of microbial mats in the geothermal band of Cerro Caliente, Deception Island (Antarctica): life at the edge of heat and cold. *Astrobiology* **19**, 1490–1504.

Lim D, Warman G, Gernhardt M, McKay C, Fong T, Marinova M and Williams D (2010) Scientific field training for human planetary exploration. *Planetary and Space Science* **58**, 920–930.

Longton RE (1967) Vegetation in the maritime Antarctic. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **252**, 213–235.

Lorenz R (2019) *Exploring Planetary Climate: A History of Scientific Discovery on Earth, Mars, Venus and Titan*. Cambridge: Cambridge University Press.

Losch A (2019) Interplanetary sustainability: Mars as a means of a long-term sustainable development of humankind in the Solar System? In Szocik K (ed.), *The Human Factor in a Mission to Mars*. Cham, Switzerland: Springer, pp. 157–166.

Luzón F, Almendros J and García-Jerez A (2011) Shallow structure of Deception Island, Antarctica, from correlations of ambient seismic noise on a set of dense seismic arrays. *Geophysical Journal International* **185**, 737–748.

Machado A, Barata T, Alves E and Cunha P (2012) Mars periglacial punctual features analyses. *Planetary and Space Science* **72**, 53–61.

Mangold N (2005) High latitude patterned grounds on Mars: classification, distribution and climatic control. *Icarus* **174**, 336–359.

Mangold N, Baratoux D, Arnalds O, Bardintzeff JM, Platevoet B, Grégoire M and Pinet P (2011) Segregation of olivine grains in volcanic sands in Iceland and implications for Mars. *Earth and Planetary Science Letters* **310**, 233–243.

Marchant D and Head J (2007) Antarctic Dry Valleys: microclimate zonation, variable geomorphic processes, and implications for assessing climate change on Mars. *Icarus* **192**, 187–222.

Marín-Tovar Y, Serrano-Posada H, Díaz-Vilchis A and Rudiño-Piñera E (2022) PCNA from *Thermococcus gammatolerans*: a protein involved in chromosomal DNA metabolism intrinsically resistant at high levels of ionizing radiation. *Proteins* **90**, 1684–1698.

Marlow JJ, Martins Z and Sephton MA (2008) Mars on Earth: soil analogues for future Mars missions. *Astronomy & Geophysics* **49**, 2–20.

Martí J and Baraldo A (1990) Pre-caldera pyroclastic deposits of Deception Island (South Shetland Islands). *Antarctic Science* **2**, 345–352.

Martí J, Vila J and Rey J (1996) Deception Island (Bransfield Strait, Atarctica): an example of a volcanic caldera developed by extensional tectonics. *Geological Society, London, Special Publications* **110**, 253–265.

Martí J, Geyer A and Aguirre-Diaz G (2013) Origin and evolution of the Deception Island caldera (South Shetland Islands, Antarctica). *Bulletin of Volcanology* **75**, 1–18.

Martins Z, Cottin H, Kotler JM, Carrasco N, Cockell C, De la Torre R, Demets R, de Vera JP, d'Hendecourt L, Ehrenfreund P, Elsaesser A, Foing B, Onofri S, Quinn R, Rabbow E, Rettberg P, Ricco A, Slenzka K, Stalport F, ten Kate I, van Loon J and Westall F (2017) Earth as a tool for astrobiology – a European perspective. *Space Science Reviews* **209**, 43–81.

Masello JF, Barbosa A, Kato A, Mattern T, Medeiros R, Stockdale JE, Kümmel M, Bustamante P, Belliure J, Benzal J, Colominas-Ciuró R, Menéndez-Blázquez J, Griep S, Goesmann A, Symondson W and Quillfeldt P (2021) How animals distribute themselves in space: energy landscapes of Antarctic avian predators. *Movement Ecology* **9**, 24.

Mateo-Martí E, Prieto-Ballesteros O, Sobrado JM, Gómez-Elvira J and Martín-Gago JA (2006) A chamber for studying planetary environments and its applications to astrobiology. *Measurement Science and Technology* **17**, 2274–2280.

Matsubara T, Fujishima K, Saltikov C, Nakamura S and Rothschild L (2017) Earth analogues for past and future life on Mars: isolation of perchlorate resistant halophiles from Big Soda Lake. *International Journal of Astrobiology* **16**, 218–228.

Matsuoka K, Skoglund A and Roth G (2018) *Quantarctica [Data set]*. Norwegian Polar Institute. https://doi.org/10.21334/npolar.2018.8516e961

McKenzie D and Nimmo F (1999) The generation of Martian floods by the melting of ground ice above dykes. *Nature* **397**, 231–233.

McLennan SM, Anderson RB, Bell III JF, Bridges JC, Calef III F, Campbell JL, Clark BC, Clegg S, Conrad P, Cousin A, Des Marais DJ, Dromart G, Dyar M D, Edgar L A, Ehlmann B L, Fabre C, Forni O, Gasnault O, Gellert R, Gordon S, Grant J A, Grotzinger J P, Gupta S, Herkenhoff K E, Hurowitz J A, King P L, Le Mouélic S, Leshin L A, Léveillé R, Lewis K W, Mangold N, Maurice S, Ming D W, Morris R V, Nachon M, Newsom H E, Ollila A M, Perrett G M, Rice MS, Schmidt M E, Schwenzer S P, Stack K, Stolper E M, Sumner D Y, Treiman A H, VanBommel S, Vaniman D T, Vasavada A, Wiens R C, Yingst R A, Science Team MSL, Kemppinen O, Bridges N, Johnson J R, Minitti M, Cremers D, Farmer J, Godber A, Wadhwa M, Wellington D, McEwan I, Newman C, Richardson M, Charpentier A, Peret L, Blank J, Weigle G, Li S, Milliken R, Robertson K, Sun V, Baker M, Edwards C, Farley K, Griffes J, Miller H, Newcombe M, Pilorget C, Siebach K, Brunet C, Hipkin V, Marchand G, Sobrón-Sánchez P, Favot L, Cody G, Steele A, Flückiger L, Lees D, Nefian A, Martin M, Gailhanou M, Westall F, Israël G, Agard C, Baroukh J, Donny C, Gaboriaud A, Guillemot P, Lafaille V, Lorigny E, Paillet A, Pérez R, Saccoccio M, Yana C, Armiens-Aparicio C, Caride-Rodríguez J, Carrasco-Blázquez I, Gómez-Gómez F, Gómez-Elvira J, Hettrich S, Lepinette-Malvitte A, Marín-Jiménez M, Martínez-Frías J, Martín-Soler J, Martín-Torres F J, Molina-Jurado A, Mora-Sotomayor L, Muñoz-Caro G, Navarro-López S, Peinado-González V, Pla-García J, Rodriguez-Manfredi J A, Romeral-Planelló J J, Sans-Fuentes S, Martinez E, Torres-Redondo J, Urqui-O'Callaghan R, Zorzano-Mier M P, Chipera S, Lacour J L, Mauchien P, Sirven J B, Manning H, Fairén A, Hayes A, Joseph J, Squyres S, Sullivan R, Thomas P, Dupont A, Lundberg A, Melikechi N, Mezzacappa A, DeMarines J, Grinspoon D, Reitz G, Prats B, Atlaskin E, Genzer M, Harri A M, Haukka H, Kahanpää H, Kauhanen J, Kemppinen O, Paton M, Polkko J, Schmidt W, Siili T, Wray J, Wilhelm M B, Poitrasson F, Patel K, Gorevan S, Indyk S, Paulsen G, Bish D, Schieber J, Gondet B, Langevin Y, Geffroy C, Baratoux D, Berger G, Cros A, d'Uston C, Lasue J, Lee Q M, Meslin P Y, Pallier E, Parot Y, Pinet P, Schröder S, Toplis M, Lewin E, Brunner W, Heydari E, Achilles C, Oehler D, Sutter B, Cabane M, Coscia D, Israël G, Szopa C, Robert F, Sautter V, Buch A, Stalport F, Coll P, François P, Raulin F, Teinturier S, Cameron J, DeLapp D, Dingler R, Jackson R, Johnstone S, Lanza N, Little C, Nelson T, Williams R, Jones A, Kirkland L, Baker B, Cantor B, Caplinger M, Davis S, Duston B, Edgett K, Fay D, Hardgrove C, Harker D, Herrera P, Jensen E, Kennedy M R, Krezoski G, Krysak D, Lipkaman L, Malin M, McCartney E, McNair S, Nixon B, Posiolova L, Ravine M, Salamon A, Saper L, Stoiber K, Supulver K, Van Beek J, Van Beek T, Zimdar R, French K, Iagnemma K, Miller K, Summons R, Goesmann F, Goetz W, Hviid S, Johnson M, Lefavor M, Lyness E, Breves E, Fassett C, Blake D, Bristow T, Edwards L, Haberle R, Hoehler T, Hollingsworth J, Kahre M, Keely L, McKay C, Wilhelm M B, Bleacher L, Brinckerhoff W, Choi D, Dworkin J, Eigenbrode J, Floyd M, Freissinet C, Garvin J, Glavin D, Harpold D, Jones A, Mahaffy P, Martin D, McAdam A, Pavlov A, Raaen E, Smith M, Stern J, Tan F, Trainer M, Meyer M, Posner A, Voytek M, Anderson R, Aubrey A, Beegle L, Behar A, Blaney D, Brinza D, Christensen L, Crisp J, DeFlores L, Ehlmann B, Feldman J, Feldman S, Flesch G, Jun I, Keymeulen D, Maki J, Mischna M, Morookian J M, Parker T, Pavri B, Schoppers M, Sengstacken A, Simmonds J, Spanovich N, de la Torre-Juarez M, Webster C, Yen A, Archer P, Cucinotta J, Jones J, Niles P, Rampe E, Nolan T, Fisk M, Radziemski L, Barraclough B, Bender S, Berman D, Dobrea E N, Tokar R, Williams R, Cleghorn T, Huntress W, Manhès G, Hudgins J, Olson T, Stewart N, Sarrazin P, Vicenzi E, Wilson S, Bullock M, Ehresmann B, Hamilton V, Hassler D, Peterson J, Rafkin S, Zeitlin C, Fedosov F, Golovin D, Karpushkina N, Kozyrev A, Litvak M, Malakhov A, Mitrofanov I, Mokrousov M, Nikiforov S, Prokhorov V, Sanin A, Tretyakov V, Varenikov A, Vostrukhin A, Kuzmin R, Wolff M, Botta O, Drake D, Bean K, Lemmon M, Lee E M, Sucharski R, de Pablo-Hernández M A, Blanco-Ávalos J J, Ramos Miguel, Kim M H, Malespin C, Plante I, Muller J P, Navarro-González R, Ewing R, Boynton W, Downs R, Fitzgibbon M, Harshman K, Morrison S, Dietrich W, Kortmann O, Palucis M, Williams A, Lugmair G, Wilson M, Rubin D, Jakosky B, Balic-Zunic T, Frydenvang J, Jensen J K, Kinch K, Koefoed A, Madsen M B, Svane-Stipp S L, Boyd N, Pradler I, Jacob S, Owen T, Rowland S, Atlaskin E, Savijärvi H, Boehm E, Böttcher E, Burmeister S, Guo J, Köhler J, Martín-García C, Mueller-Mellin R, Wimmer-Schweingruber R, McConnochie T, Benna M, Franz H, Bower H, Brunner A, Blau H, Boucher T, Carmosino M, Atreya S, Elliott H, Halleaux D, Rennó N, Wong M, Pepin R, Elliott B, Spray J, Thompson L, Williams J, Vasconcelos P, Bentz J, Nealson K, Popa R, Kah L, Moersch J, Tate C, Day M, Kocurek G, Hallet B, Sletten R, Francis R, McCullough E, Cloutis E, ten Kate I L, Kuzmin R, Arvidson R, Fraeman A, Scholes D, Slavney S, Stein T, Ward J, Berger J and Moores J (2013) Elemental geochemistry of sedimentary rocks at Yellowknife Bay, Gale crater, Mars. *Science* **343**, 1–15.

McLoughlin N, Wacey D, Kruber C, Kilburn MR, Thorseth IH and Pedersen RB (2011) A combined TEM and NanoSIMS study of endolithic microfossils in altered seafloor basalt. *Chemical Geology* **289**, 154–162.

McSween HY, Arvidson RE, Bell JF, Blaney D, Cabrol NA, Christensen PR, Clark BC, Crisp JA, Crumpler LS, Des Marais DJ, Farmer JD, Gellert R, Ghosh A, Gorevan S, Graff T, MorrisGrant J, Haskin LA, Herkenhoff KE, Johnson JR, Jolliff BL, Klingelhoefer G, Knudson AT, McLennan S, Milam KA, Moersch JE, Morris RV, Rieder R, Ruff SW, de Souza PA, Squyres SW, WaÌˆnke H, Wang A, Wyatt MB, Yen A and Zipfel JJ (2004) Basaltic rocks analyzed by the Spirit Rover in Gusev Crater. *Science* **305**, 842–845.

McSween HY, Ruff SW, Morris RV, Bell III JF, Herkenhoff K, Gellert R, Stockstill KR, Tornabene LL, Squyres SW, Crisp JA, Christensen PR, McCoy TJ, Mittlefehldt DW and Schmidt M (2006) Alkaline volcanic rocks from the Columbia Hills, Gusev Crater, Mars. *Journal of Geophysical Research: Planets* **111**, E09S91.

McSween Jr, HY, Taylor GJ and Wyatt MB (2009) Elemental composition of the Martian crust. *Science* **324**, 736–739.

Meeßen J, Wuthenow P, Schille P, Rabbow E, de Vera J-P and Ott S (2015) Resistance of the lichen *Buellia frigida* to simulated space conditions during the preflight tests for BIOMEX – viability assay and morphological stability. *Astrobiology* **15**, 601–615.

Meslier V and DiRuggiero J (2019) Endolithic microbial communities as model systems for ecology and astrobiology. In Seckbach J and Rampelotto P (eds), *Model Ecosystems in Extreme Environments*. London, UK: Elsevier Inc: Academic Press, pp. 145–168.

Metzger P, Britt D, Covey S and Lewis JS (2017) Figure of merit for asteroid regolith simulants. In European Planetary Science Congress.

Millan M, Williams A, McAdam A, Eigenbrode J, Steele A, Freissinet C, Glavin DP, Szopa C, Buch A, Summons RE, Lewis JM, Wong GM, House CH, Sutter B, McIntosh O, Bryk AB, Franz HB, Pozarycki C, Stern JC, Navarro-Gonzalez R, Archer DP, Fox V, Bennett K, Teinturier S, Malespin C, Johnson SS and Mahaffy PR (2022) Sedimentary organics in Glen Torridon, Gale crater, Mars: results from the SAM instrument suite and supporting laboratory analyses. *JGR Planets* **127**, e2021JE007107.

Ming DW, Gellert R, Morris RV, Arvidson RE, Brückner J, Clark BC, Cohen BA, D'Uston C, Economou T, Fleischer I, Klingelhöfer G, McCoy TJ, Mittlefehldt DW, Schmidt ME, Schröder C, Squyres SW, Tréguier E, Yen AS and Zipfel J (2008) Geochemical properties of rocks and soils in Gusev Crater, Mars: results of the alpha particle X-ray spectrometer from Cumberland ridge to home plate. *Journal of Geophysical Research* **113**, E12S39.

Minitti ME and Hamilton VE (2010) A search for basaltic-to-intermediate glasses on Mars: assessing Martian crustal mineralogy. *Icarus* **210**, 135–149.

Mitchell K and Wilson L (2003) Mars: a geologically active planet. *Astronomy and Geophysics* **44**, 16–20.

Mittlefehldt DW, Gellert R, McCoy T, McSween Jr. HY and Li R (2006) Possible Ni-rich mafic–ultramafic magmatic sequence in the Columbia Hills: evidence from the Spirit Rover. 37th Lunar and Planetary Science Conference. Houston: LPSC.

Molina A, de Pablo M and Ramos M (2013) Deception Island, Antarctica, an Earth–Mars Analogue. 44th Lunar and Planetary Science Conference (p. 1202).

Molina A, de Pablo M and Ramos M (2014) Deception Island (Antarctica) as an Earth–Mars geomorphological analogue. Book of Abstracts of EUCOP4 – 4th European Conference on Permafrost (p. 250). Évora. doi: 10.13140/2.1.4158.9127.

Moller R, Jandura L, Rosette K, Robinson M, Samuels J, Silverman M, ,Brown K, Duffy E, Yazzie A, Jens E, Brockie I, White L, Goreva Y, Zorn T, Okon A, Lin J, Frost M, Collins C, Williams J, Steltzner A, Chen F and Biesiadecki J (2021) The sampling and caching subsystem (SCS) for the scientific exploration of Jezero Crater by the Mars 2020 Perseverance Rover. *Space Science Reviews* **217**, 1–43.

Morris R, Golden D, Ming D, Shelfer T, Jorgensen L, Bell J, Graff TG and Mertzman SA (2001) Phyllosilicate-poor palagonitic dust from Mauna Kea Volcano (Hawaii): a mineralogical analogue for magnetic Martian dust? *Journal of Geophysical Research* **106**, 5057–5083.

Morris RV, Klingelhöfer G, Bernhardt B, Schröder C, Rodionov DS, de Souza Jr, PA, Yen A, Gellert R, Evlanov EN, Foh J, Kankeleit E, Gütlich P, Ming DW, Renz F, Wdowiak T, Squyres SW and Arvidson RE (2004) Mineralogy at Gusev crater from the Mossbauer spectrometer on the Spirit rover. *Science* **305**, 833–836.

Morrison S, Downs R, Blake D, Vaniman D, Ming D, Hazen R and Rampe E (2018) Crystal chemistry of Martian minerals from Bradbury Landing through Naukluft Plateau, Gale crater, Mars. *American Mineralogist: Journal of Earth and Planetary Materials* **103**, 857–871.

Motamedi Mohammadabadi K (2013) *Validating the Performance of a Raman Laser Spectrometer (RLS) Instrument under Martian Conditions* (PhD thesis). Vrije Universiteit Amsterdam, Amsterdam.

Mouginis-Mark PJ (2021) What makes a great terrestrial planetary analog? Terrestrial Analogs 2021 (LPI Contrib. No. 2595) (p. 8021). Virtual: Lunar and Planetary Institute.

Muñoz PA, Flores PA, Boehmwald FA and Blamey JM (2011) Thermophilic bacteria present in a sample from Fumarole Bay, Deception Island. *Antarctic Science* **23**, 549–555.

Musilova M, Wright G, Ward J and Dartnell L (2015) Isolation of radiation-resistant bacteria from Mars analog Antarctic Dry Valleys by preselection, and the correlation between radiation and desiccation resistance. *Astrobiology* **15**, 1076–1090.

National Aeronautics and Space Administration (NASA) (2015) *Astrobiology Strategy.* Washington, DC: National Aeronautics and Space Administration-NASA.

Navarro-González R (2005) Búsqueda de vida en Marte. *TIP. Revista especializada en ciencias químico-biológicas* **8**, 82–90.

Navarro-González R, Rainey F, Molina P, Bagaley D, Hollen B, de la Rosa J and McKay C (2003) Mars-like soils in the Atacama desert, Chile, and the dry limit of microbial life. *Science* **302**, 1018–1021.

Nicholson W, Krivushin K, Gilichinsky D and Schuerger A (2013) Growth of *Carnobacterium* spp. from permafrost under low pressure, temperature, and anoxic atmosphere has implications for Earth microbes on Mars. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 666–671.

Nie N, Dauphas N, Villalon K, Liu N, Heard A, Morris R and Mertzman S (2020) Iron isotopic and chemical tracing of basalt alteration and hematite spherule formation in Hawaii: a prospective study for Mars. *Earth and Planetary Science Letters* **544**, 116385.

Ogawa Y, Yamagishi Y and Kurita K (2003) Evaluation of melting process of the permafrost on Mars: its implication for surface features. *Journal of Geophysical Research: Planets* **108**, 8046.

Oliva-Urcia B, Gil-Peña I, Maestro A, López-Martínez J, Galindo-Zaldívar J, Soto R, Gil-Imaz A and Pueyo O (2016) Paleomagnetism from Deception Island (South Shetlands archipelago, Antarctica), new insights into the interpretation of the volcanic evolution using a geomagnetic model. *International Journal of Earth Sciences* **105**, 1353–1370.

Ollila A, Newsom H, Clark B, Wiens R, Cousin A, Blank J, Mangold N, Sautter Sautter, Maurice S, Clegg SM, Gasnault O, Forni O, Tokar R, Lewin E, Dyar MD, Lasue J, Anderson R, McLennan S, Bridges J, Vaniman D, Lanza N, Fabre C, Melikechi N, Perrett G, Campbell J, King P, Barraclough B, Delapp D, Johnstone S, Meslin PY, Rosen-Gooding A, Williams J and The MSL Science Team (2014) Trace element geochemistry (Li, Ba, Sr, and Rb) using Curiosity's ChemCam: early results for Gale crater from Bradbury Landing Site to Rocknest. *JGR Planets* **119**, 255–285.

Orgel C, Kereszturi Á, Váczi T, Groemer G and Sattler B (2014) Scientific results and lessons learned from an integrated crewed Mars exploration simulation at the Rio Tinto Mars analogue site. *Acta Astronautica* **94**, 736–748.

Orosei R, Lauro S, Pettinelli E, Cicchetti A, Coradini M, Cosciotti B, Di Paolo F, Flamini E, Mattei E, Pajola M, Soldovieri F, Cartacci M, Cassenti F, Frigeri A, Giuppi S, Martufi R, Masdea A, Mitri G, Nenna C, Noschese R, Restano M and Seu R (2018) Radar evidence of subglacial liquid water on Mars. *Science* **361**, 490–493.

Pantazidis A, Baziotis I, Solomonidou A, Manoutsoglou E, Palles D, Kamitsos E, Karageorgis A, Profitiliotis G, Kondoyanni M, Klemme S, Berndt J, Ming D and Asimow P (2019) Santorini volcano as a potential Martian analogue: the Balos Cove Basalts. *Icarus* **325**, 128–140.

Parro V, Fernández-Remolar D, Rodríguez-Manfredi J, Cruz-Gil P, Rivas L, Ruíz-Bermejo M and Menor-Salván C (2011) Classification of modern and old Río Tinto sedimentary deposits through the biomolecular record using a life marker biochip: implications for detecting life on Mars. *Astrobiology* **11**, 29–44.

Parro V, Puente-Sánchez F, Cabrol N, Gallardo-Carreño I, Moreno-Paz M, Blanco Y, García-Villadangos M, Tambley C, Tilot V, Thompson C, Smith E, Sobrón P, Demergasso C, Echeverría-Vega A, Fernández-Martínez MA, Whyte LG and Fairén A (2019) Microbiology and nitrogen cycle in the benthic sediments of a glacial oligotrophic deep Andean lake as analog of ancient Martian lake-beds. *Frontiers in Microbiology* **10**, 929.

Pérez M, Lorenzo D and Delgado M (2013) Viabilidad de semillas de arroz provenientes de plantas obtenidas in vitro. *Acta agronómica* **62**, 114–119.

Pommerol A, Thomas N, Jost B, Beck P, Okubo C and McEwen A (2013) Photometric properties of Mars soils analogs. *Journal of Geophysical Research: Planets* **118**, 2045–2072.

Price A, Macey M, Pearson V, Schwenzer S, Ramkissoon N and Olsson-Francis K (2022) Oligotrophic growth of nitrate-dependent Fe^{2+}-oxidising microorganisms under simulated early Martian conditions. *Frontiers in Microbiology* **13**, 800219.

Prieto-Ballesteros O, García M, Rodríguez-Manfredi JA, Gómez F, Blanco Y and Parro V (2010) Antarctic permafrost studies for testing the Signs Of Life Detector (SOLID). European Planetary Science Congress (p. 601). Roma.

Ramos M, de Pablo M, Sebastian E, Armiens C and Gómez-Elvira J (2012) Temperature gradient distribution in permafrost active layer, using a prototype of the ground temperature sensor (REMS-MSL) on Deception Island (Antarctica). *Cold Regions Science and Technology* **72**, 23–32.

Rampe E, Blake D, Bristow T, Ming D, Vaniman D, Morris R and Wiens R (2020) Mineralogy and geochemistry of sedimentary rocks and eolian sediments in Gale Crater, Mars: a review after six Earth years of exploration with Curiosity. *Geochemistry* **80**, 125605.

Reese C and Solomatov V (2006) Fluid dynamics of local Martian magma oceans. *Icarus* **184**, 102–120.

Reese C, Orth C and Solomatov V (2011) Impact megadomes and the origin of the Martian crustal dichotomy. *Icarus* **213**, 433–442.

Rickman D, Hoelzer H, Fourroux K, Owens C, McLemore C and Fikes J (2007) Quantitative technique for comparing simulant materials through figures of merit. In Planetary and Mining Science Symposium.

Rickman DL, Hoelzer H and Fourroux K (2009) *Lunar Regolith Figures of Merit*. NASA.

Rieder R, Gellert R, Anderson R, Brückner J, Clark B, Dreibus G, Economou T, Klingelhöfer G, Lugmair GW, Ming DW, Squyres SW, d'Uston C, Wänke H, Yen A and Zipfel J (2004) Chemistry of rocks and soils at Meridiani Planum from the alpha particle X-ray spectrometer. *Science* **306**, 1746–1749.

Rogers AD and Hamilton VE (2015) Compositional provinces of Mars from statistical analyses of TES, GRS, OMEGA and CRISM data. *Journal of Geophysical Research: Planets* **120**, 62–91.

Román A, Navarro G, Caballero I and Tovar-Sánchez A (2022) High-spatial resolution UAV multispectral data complementing satellite imagery to characterize a chinstrap penguin colony ecosystem on Deception Island (Antarctica). *GIScience & Remote Sensing* **59**, 1159–1176.

Ruff S and Christensen P (2007) Basaltic andesite, altered basalt, and a TES-based search for smectite clay minerals on Mars. *Geophysical Research Letters* **34**, 1–6.

Rumpf M, Needham H and Fagents S (2020) Thicknesses of lava flows in satellite images: comparison of layered mare units with terrestrial analogs. *Icarus* **350**, 113853.

Sajjad W, Ilahi N, Kang S, Bahadur A, Zada S and Iqbal A (2022) Endolithic microbes of rocks, their community, function and survival strategies. *International Biodeterioration & Biodegradation* **169**, 105387.

Sauro F, Pozzobon R, Massironi M, de Berardinis P, Santagata T and Waele J (2020) Lava tubes on Earth, Moon and Mars: a review on their size and morphology revealed by comparative planetology. *Earth-Science Reviews* **209**, 103288.

Sautter V, Fabre C, Forni O, Toplis M, Cousin A, Ollila A, Meslin P, Maurice S, Wiens R, Baratoux D, Mangold N, Le Mouélic S, Gasnault O, Berger G, Lasue J, Anderson R, Lewin E, Schmidt M, Dyar D, Ehlmann B, Bridges J, Clark B and Pinet P (2013) Igneous mineralogy at Bradbury Rise: the first ChemCam campaign at Gale Crater. *JGR Planets* **119**, 30–46.

Schmidt ME, Schrader CM and McCoy TJ (2013) The primary fO2 of basalts examined by the Spirit rover in Gusev Crater, Mars: Evidence for multiple redox states in the Martian interior. *Earth and Planetary Science Letters* **384**, 198–208.

Schwendner P, Cockell C, Rettberg P, Beblo-Vranesevic K, Bohmeir M, Rabbow E, Westall F, Gaboyer F, Walter N, Cabezas P, Moissl-Eichinger C, Perras A, Gomez F, Malki M, Amils R, Garcia-Descalzo L, Ehrenfreund P, Monaghan E, Marteinsson V and Vannier P (2016) Metabolic response of Yersinia MASE-LGI to osmotic stress and ionizing radiation. European Astrobiology Network Association annual conference (pp. ME-SBA). Athens: EANA.

Seelos K, Arvidson R, Jolliff B, Chemtob S, Morris R, Ming D and Swayze G (2010) Silica in Mars analog environment: Ka'u Desert, Kilauea Volcano, Hawaii. *Journal of Geophysical Research Atmospheres* **115**, 1–18.

Shtarkman Y, Koçer Z, Edgar R, Veerapaneni R, D'Elia T, Morris P and Rogers S (2013) Subglacial Lake Vostok (Antarctica) accretion ice contains a diverse set of sequences from aquatic, marine and sediment-inhabiting bacteria and eukarya. *PLoS ONE* **8**, 1–13.

Sleep N and Zahnle K (2001) Carbon dioxide cycling and implications for climate on ancient Earth. *Journal of Geophysical Research* **106**, 1373–1399.

Smellie JL (1988) Recent observations on the volcanic history of Deception Island, South Shetland Islands. *British Antarctic Survey Bulletin* **81**, 83–85.

Smellie JL and Edwards BR (2016) *Glaciovolcanism on Earth and Mars*. Cambridge: Cambridge University Press.

Smith RL (2005) The thermophilic bryoflora of Deception Island: unique plant communities as a criterion for designating an Antarctic Specially Protected Area. *Antarctic Science* **17**, 17–27.

Smith R, McLennan S, Achilles C, Dehouck E, Horgan B, Mangold N, Rampe E, Salvatore M, Siebach K and Sun V (2021) X-ray amorphous components in sedimentary rocks of Gale Crater, Mars: evidence for ancient formation and long-lived aqueous activity. *JGR Planets* **126**, e2020JE006782.

Soffen G (1977) The Viking project. *Journal of Geophysical Research* **82**, 3959–3970.

Squyres S, Arvidson R, Bell III J, Brückner J, Cabrol N, Calvin W and Yen A (2004) The Opportunity Rover's Athena science investigation at Meridiani Planum, Mars. *Science* **306**, 1698–1703.

Squyres SW, Arvidson RE, Blaney DL, Clark BC, Crumpler L, Farrand WH, Gorevan S, Herkenhoff KE, Hurowitz J, Kusack A, McSween HY, Ming DW, Morris RV, Ruff SW, Wang A and Yen A (2006) Rocks of the Columbia Hills. *Journal of Geophysical Research – Planets* **111**, E02S11.

Squyres SW, Aharonson O, Clark BC, Cohen BA, Crumpler L, de Souza PA, Farrand WH, Gellert R, Grant J, Grotzinger JP, Haldemann AFC, Johnson JR, Klingelhofer G, Lewis KW, Li R, McCoy T, McEwen AS, McSween HY, Ming DW, Moore JM, Morris RV, Parker TJ, Rice JW, Ruff S, Schmidt M, Schroder C, Soderblom LA and Yen A (2007) Pyroclastic activity at home plate in Gusev Crater, Mars. *Science* **316**, 738–742.

Stanley SO and Rose AH (1967) Bacteria and yeasts from lakes on Deception Island. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **252**, 199–207.

Sulcanese D, Mitri G, Genova A, Petricca F, Andolfo S and Chiarolanza G (2023) Topographical analysis of a candidate subglacial water region in Ultimi Scopuli, Mars. *Icarus* **392**, 115394.

Szocik K, Marques RE, Abood S, Kędzior A, Lysenko-Ryba K and Minich D (2018) Biological and social challenges of human reproduction in a long-term Mars base. *Futures* **100**, 56–62.

Thomas T and Hu R (2019) *Evolution History of the Isotopic Composition of Nitrogen in the Martian Atmosphere*. Pasadena: Ninth International Conference on Mars LPI.

Tirsch D, Craddock R, Platz T, Maturilli A, Helbert J and Jaumann R (2012) Spectral and petrologic analyses of basaltic sands in Ka'u Desert (Hawaii) – implications for the dark dunes on Mars. *Earth Surface Processes and Landforms* **37**, 434–448.

Tovar D, de Pablo-Hernández MA, Leal MA, Tchegliakova N, Molina A, Leone G, San Martín J, Sánchez J, Torres A and Bonilla A (2024) Gorgona Island as a geochemical terrestrial analog. In 55th Lunar and Planetary Science Conference, LPI Contributions, p. 1539.

Udry A, Howarth GH, Herd CDK, Day JM, Lapen TJ and Filiberto J (2020) What Martian meteorites reveal about the interior and surface of Mars. *Journal of Geophysical Research: Planets* **125**, 1–34.

Usui T, McSween HY and Clark BC (2008) Petrogenesis of high-phosphorous Wishstone Class rocks in Gusev Crater, Mars. *Journal of Geophysical Research* **113**, E12S44.

Valencio DA, Mendía J and Vilas JF (1979) Palaeomagnetism and K–Ar age of Mesozoic and Cenozoic igneous rocks from Antarctica. *Earth and Planetary Science Letters* **45**, 61–68.

Verseux C, Baqué M, Lehto K, de Vera J, Rothschild L and Billi D (2016) Sustainable life support on Mars – the potential roles of cyanobacteria. *International Journal of Astrobiology* **15**, 65–92.

Vicente J, de Celis M, Alonso A, Marquina D and Santos A (2021) Microbial communities present in hydrothermal sediments from Deception Island, Antarctica. *Microorganisms* **9**, 1–14.

Villanueva GL, Mumma MJ, Novak RE, Käufl HU, Hartogh P, Encrenaz T, Tokunaga A, Khayat A and Smith MD (2015) Strong water isotopic anomalies in the martian atmosphere: Probing current and ancient reservoirs. *Science* **348**, 218–221.

Wamelink G, Frissel J, Krijnen W and Verwoert M (2019) Crop growth and viability of seeds on Mars and Moon soil simulants. *Open Agriculture* **4**, 509–516.

West M, Clarke J, Laing J, Willson D, Waldie J, Murphy G, Thomas M and Mann G (2010*a*) Testing technologies and strategies for exploration in Australian Mars analogues: a review. *Planetary and Space Science* **58**, 658–670.

West M, Clarke J, Thomas M, Pain C and Walter M (2010*b*) The geology of Australian Mars analogue sites. *Planetary and Space Science* **58**, 447–458.

Wierzchos J, Sancho LG and Ascaso C (2005) Biomineralization of endolithic microbes in rocks from the McMurdo Dry Valleys of Antarctica: implications for microbial fossil formation and their detection. *Environmental Microbiology* **7**, 566–575.

Wilson L and Head JW (2002) Heat transfer and melting in subglacial basaltic volcanic eruptions: implications for volcanic deposit morphology and meltwater volumes. In Smellie JS and Chapman MG (eds), *Geological Society, Volcano–Ice Interactions on Earth and Mars*. Londres: Geological Society – Special Publications, pp. 5–26.

Wilson L, Smellie JL and Head JW (2013) Volcano–ice interactions. In Fagents SA, Gregg TKP and Lopes RMC (eds), *Modeling Volcanic Processes: The Physics and Mathematics of Volcanism*. Cambridge: Cambridge University Press, pp. 275–299.

Wyatt MB and McSween HY (2002) Spectral evidence for weathered basalt as an alternative to andesite in the northern lowlands of Mars. *Nature* **417**, 263–266.

Yen AS, Gellert R, Schröder C, Morris RV, Bell III, JF, Knudson AT, Clark BC, Ming DW, Crisp JA, Arvidson RE, Blaney D, Brückner J, Christensen PR, DesMarais DJ, de Souza Jr, PA, Economou TE, Ghosh A, Hahn BC, Herkenhoff KE, Haskin LA, Hurowitz JA, Joliff BL, Johnson JR, Klingelhöfer G, Madsen MB, McLennan SM, McSween HY, Richter L, Rieder R, Rodionov D, Soderblom L, Squyres SW, Tosca NJ, Wang A, Wyatt M and Zipfel J (2005) An integrated view of the chemistry and mineralogy of martian soils. *Nature* **436**, 49–54.

Yin A (2012) Structural analysis of the Valles Marineris fault zone: possible evidence for large-scale strike-slip faulting on Mars. *Lithosphere* **4**, 286–330.

Yin A, Moon S and Day M (2021) Landform evolution of Oudemans Crater and its bounding plateau plains on Mars: geomorphological constraints on the Tharsis ice-cap hypothesis. *Icarus* **360**, 114332.