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Validation of astrobiology technologies and instrument operations in terrestrial analogue environments

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Abstract

Terrestrial analogue environments are places on Earth that present geological or environmental conditions that are similar to those found on an extraterrestrial body. Analogue environments serve four functions: (1) *learn* about planetary processes on Earth and elsewhere; (2) *test* technologies, methodologies, and protocols; (3) *train* highly-qualified personnel, as well as science and operations teams; (4) *engage* the public, space agencies, media, and educators. Analogue studies also enable the development and validation of biosignatures and detection techniques. Analogue programs include the Canadian Space Agency's Canadian Analogue Research Network, NASA's Astrobiology Science and Technology for Exploring Planets, and NASA's Analog Missions. Examples of technology and instrument testing and validation in analogue environments include the Haughton-Mars Project Research Station, the Arctic Mars Analog Svalbard Expedition (AMASE), the Rio Tinto basin, and NASA's Field Integrated Design and Operations (FIDO). ***To cite this article: R. Léveillé, C. R. Palevol 8 (2009).***

Résumé

Validation de technologies et d'instrumentation en astrobiologie dans des environnements analogues terrestres. Les environnements terrestres analogues sont des endroits sur Terre qui possèdent des conditions géologiques ou environnementales semblables à celles d'un corps extraterrestre. L'étude des environnements analogues permet : (1) de mieux connaître les processus planétaires terrestres et extraterrestres ; (2) de tester des technologies, des méthodologies et des protocoles ; (3) de former du personnel hautement qualifié, ainsi que des équipes scientifiques et opérationnelles ; (4) d'attirer l'attention du public, des agences spatiales, des médias et des enseignants. Les études dites analogues permettent également de développer et de tester des techniques de détection de biosignatures. Les *Canadian Space Agency's Canadian Analogue Research Network, NASA's Astrobiology Science and Technology for Exploring Planets* et les *NASA's Analog Missions* sont des exemples de programmes analogues. Des exemples de tests et de validation de technologies et d'instruments dans les environnements analogues comprennent les *Haughton-Mars Project Research Station, Arctic Mars Analog Svalbard Expedition (AMASE), Rio Tinto basin* et *NASA's Field Integrated Design and Operations (FIDO.)*. ***Pour citer cet article : R. Léveillé, C. R. Palevol 8 (2009).***

Keywords: Analogue environments; Planetary exploration; Missions; Life detection; Mars; Astrobiology

Mots clés : Environnements analogues ; Exploration planétaire ; Missions ; Détection de la vie ; Mars ; Astrobiologie

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1. Introduction

Terrestrial analogue environments are places on Earth with geological or environmental conditions that are similar to those that exist on an extraterrestrial body. So-called "analogue studies" are essential to planetary exploration because they help us understand the workings of certain processes on Earth and thus to interpret and validate the data received from orbiter or surface missions to the Moon, Mars, or beyond. Analogue studies are also critical in understanding scientific and technological requirements and strategies for astrobiology-related robotic or human exploration missions. Notably, these studies can provide operational tests of instruments and technologies under relevant environmental conditions. In addition, these sites can allow validation of the ability of space instruments to function properly under conditions difficult to replicate in the laboratory and that approach the environmental or geological complexity and heterogeneity of the eventual target. Through analogue studies, technologies for astrobiology can be developed affordably and practically, thus reducing overall costs and risks associated with the development process. In this paper, examples of analogue environments and their functions are described. In addition, examples of validation of astrobiology technologies and operations in analogue environments are summarized.

2. Analogue environments

2.1. Definition and description

Terrestrial analogue environments are defined as places on Earth that present one or more sets of geological or environmental conditions similar to those found on an extraterrestrial body, current or past [48]. For example, the Dry Valleys of Antarctica, one of the coldest and driest places on Earth, demonstrate environmental conditions that are similar (but not necessarily equivalent) to the present conditions on Mars, as well as features (e.g., ground ice) that are suspected on Mars [8,16,39,62]. An analogue environment does not necessarily present all the conditions of an extraterrestrial environment. For example, the basaltic volcanoes of Hawaii are generally similar to martian volcanoes, although the Hawaiian climate is very different from that of present-day Mars. Terrestrial analogues to Mars are perhaps the most studied due to the similarities of the surfaces of the two planets [15] and the intense exploration of Mars that has occurred over the last decade. Examples of analogue environments to Mars include the polar regions (e.g., cryosphere, permafrost, ice, polar desert) [39,40,51,61], volcanic and hydrothermal systems [18,47], impact craters [15,37], hyperarid environments (e.g., Atacama desert, Chile) [45], dunes and wind-related features [15], erosional systems (e.g., valleys, gullies) [15], diagenetic/sedimentary systems (e.g., lakes and playas, iron formations, sulfates, phyllosilicates) [2,6,39,40,56], and subsurface environments [14,23,57]. Table 1 identifies several important analogue environments appropriate for astrobiology-related research and technology development.

The term *fidelity* refers to the similarity of an analogue with respect to the extraterrestrial environment to which it is compared [48,59]. Sites with many closely-related attributes are said to offer a greater fidelity. No site on Earth is identical to another extraterrestrial body in all its aspects. Thus, it must be emphasized that terrestrial locations can only be used as analogues of specific aspects of another planet, not as perfect analogues of an entire extraterrestrial environment. The study of several different analogue sites may therefore be necessary to fully understand an extraterrestrial process or the data generated during a space mission. When using a terrestrial analogue, it is important to understand what might be similar and what might be different, and to ensure that the differences do not affect the analysis for which the analogue is being used [44]. Recently, a relative metric, the Analog Value Index, has been proposed to evaluate and quantify the value of planetary analogues with respect to their fidelity, but also their applications, functions, and cost-effectiveness [36]. Qualitative estimates of different elements of fidelity (e.g., science value and operations, technology development and integration, outreach and education, etc.) have also been published [59], though the authors state that these are subjective and that difficulties exist in comparing one-time field tests with multiyear, multicomponent testing programs.

In the widest sense, the term *analogue* includes natural environments, materials (rocks, meteorites, soils, ice [50]) and laboratory/artificial environments or devices that mimic specific planetary conditions. For example, the International Space Station and space shuttle flights could all be considered microgravity analogue environments. Similarly, Antarctic environmental regulations can be used as analogues for planetary protection protocols developed for Mars [17]. However, for the purpose of the remainder of this chapter, analogues will refer to natural terrestrial environments only.

2.2. Functions of analogue environments

Generally, analogue environments serve four basic functions [35]:

Table 1
Examples of analogue sites to Mars featuring astrobiology research and development activities.
Tableau 1
Exemples de sites analogues de Mars comprenant des activités de recherche et de développement en astrobiologie.

Location	Main features	Infrastructure/logistics support	Astrobiology technology development	References
Devon Island, High Arctic, Canada	Haughton Impact Structure, impact-induced hydrothermal deposits, intracrater paleolacustrine deposits, polar desert, polygon terrain,	Haughton Mars Project Research Station (Mars Institute); Devon Island Research Station	DAME drill	[25,35,36,38,47]
Axel-Heiberg Island, High Arctic, Canada	Permafrost, massive ground ice, perennial cold springs, paleosprings, gullies, endoliths/hypoliths, pingos/seasonal frost mounds	McGill Arctic Research Station (McGill University); Eureka Weather Station (Environment Canada)	Fluorescent microscope Drilling	[33,43]
Ellesmere Island, High Arctic, Canada	Supraglacial sulfur springs (Borup Fjord), endoliths/hypoliths, massive ground ice, patterned ground	n/a	n/a	[28]
Pavilion Lake, British Columbia, Canada	Fresh-water microbialites	Pavilion Lake Research Project (University of British Columbia; NASA Ames)	Underwater remotely operated vehicles; *Deepworker* submersible	[34]
Northern Canadian Mines: Lupin Mine, Nunavut, Canada; Kidd Creek Mine, Ontario; Nanisivik, Nunavut	Deep subsurface microbial ecosystems, deep subsurface hydrocarbon gases, acid mine drainage	Mining installations, subsurface excavation	n/a	[57]
Svalbard, Norway	Volcanism; carbonates	AMASE (NASA ASTEP) R/V Lance	Various MSL and ExoMars instruments (e.g. CheMin, SAM); Mars cryobot prototype	[60]
Rio Tinto Basin, Spain	Acidic river and groundwater system, iron- and sulfate-rich deposits,	n/a	MARTE drill Raman	[2,13,21,22]
Dry Valleys, Antarctica	Extreme aridity, high winds, extreme low temperatures, paleolacustrine deposits, periglacial features, endoliths/hypoliths	Various research stations	n/a	[8,16,39,62]
Sub-glacial lakes, Antarctica	Several sub-ice lakes, including Lake Vostok	Various research stations	Various remote sensing operations	[24]
Atacama Desert, Chili	Extreme aridity, dry and oxidizing soils, caves	n/a	Various instruments and mobility systems	[12,45]
Western Deserts, California/Nevada/Utah/Arizona, USA	Cold desert, dry + oxidizing soils, iron concretions, endoliths/hypoliths, playas	Various	Rovers Remote sensing	[4,5,14]
Big Island, Hawaii, USA	Active and recent volcanism, volcanic features, lava tubes, solfatera	PISCES	Autonomous drill	[55]
Witwatersrand Basin, South Africa	Deep subsurface microbial ecosystems; deep subsurface hydrocarbon gases	Mining installations, subsurface excavation	n/a	[57]
Central and Western Australia	Impact craters, extremely arid desert, playas, clay pans, river networks, oldest known microfossils (Pilbara), microbialites, acid lakes	Various	n/a	[1,7]
Northern Africa	Buried river networks and craters (Egypt); playas and evaporates, episodic discharge (Tunisia)	Ibn Battuta Centre	GPR	[6,30,46]

n/a: information not available or not relevant to location.

- *learn* about planetary processes on Earth and elsewhere;
- *test* methodologies, protocols, strategies, and technologies;
- *train* highly-qualified personnel, as well as science and operations teams;
- *engage* the public, space agencies, media, and educators.

These functions are described in more detail below.

2.2.1. Learn

It is widely acknowledged that analogue environments are critical to the understanding of extraterrestrial processes. Analogue studies allow us to learn about terrestrial processes and, by extrapolation, processes on extraterrestrial bodies. They also enable us to learn about the limits of both physical and biological processes on Earth, thus defining zones of habitability and providing clues to where life could be present, or may have developed elsewhere [7]. These studies also potentially lead to the discovery of novel organisms that can survive or flourish in such environments or even novel metabolic pathways. Field-based data from analogue environments can be used in computer models that further simulate specific processes on an extraterrestrial planet. Investigating basic science questions in analogue environments leads to the development of methodological and instrument requirements for future missions. These primary science requirements are essential to the proper design of space mission hardware and operations.

Terrestrial analogue studies are especially critical in the ongoing transition from global mapping missions to missions (especially with respect to Mars) focusing on detailed analyses at the regional and outcrop scale [19,20]. These missions are characterized by a sustained surface presence, and require new operations and technologies with the ability to function autonomously. Studies of analogue environments are also critical for selecting landing sites of surface missions, both with respect to science priorities and engineering/safety constraints for spacecraft [27], but also for testing and developing landing systems [29]. Similarly, analogue studies can assist in target selection and preparations for detailed remote observations for orbiter missions.

2.2.2. *Test*

Analogue studies are essential to the testing and validation of space technologies and science instruments, as well as their successful operation [44,48]. Researchers can test science instruments, rovers, robotic systems, spacesuits and other technologies, and evaluate experimental procedures to see how these elements operate in an often remote and (or) hostile environment. The technical feasibility and potential of an instrument, or a specific methodology, can be demonstrated (i.e., proof-of-concept) in analogue environments prior to selection for a mission [49,58]. This usually includes demonstrating the scientific rewards and limitations of a chosen instrument or methodology. Existing technologies, off-the-shelf instruments, and prototypes are useful for supporting the development of flight hardware. In particular, different models and multiple units can be field tested in a number of different environments and settings at a relatively low cost. Through progressive iterations, one can assess what works and what needs to be developed or improved. Typically, deployment and validation of science instruments in different environments also demonstrate the importance of relevant and well-studied standards and the requirements for appropriate spectral databases [63].

Analogue studies can also be used to test the wear on hardware in realistic operating conditions [5]. The ground truthing in suitable analogue sites should be required during the test phases of space instrumentation. Analogues can also act as testbeds for crucial real-time problem solving during missions. For example, the Mars Exploration Rovers (MER) mobility issues were solved by trying out various strategies in a simulated “Mars yard”. Analogue environments can also be essential to understand data returned from missions, as in the case of the search for terrestrial equivalents [14] of the martian “blueberry” – like concretions discovered by the MER *Opportunity*.

Analogue environments are particularly suitable for demonstrating systems integration (e.g., a rover with a mounted drill system) or system-of-system capabilities where several technologies are required to function together. Integrating robotic science experiments with a high level of realism and integration can provide significant insights to component technology capabilities and operational limitations, but also give serendipitous findings about operational strategies and science return [53]. Field tests enable science instrument teams to better develop interfaces and ideas for future integration with instrument platforms [65,66]. Such studies also demonstrate the relative importance of different instruments to mission objectives, as well as showing the value-added results from the integration of multiple instruments and how instruments collaboratively analyze a field site [63].

In addition to various instruments, planetary surface operations, both robotic and human, can be developed and tested in analogue environments [19]. Science teams can explore measurement strategies and sample-handling and sample-collection protocols [42] with realistic power and scheduling constraints in order to understand the operational requirements for a future mission. Analogue studies can progressively add mission realism and complexity (e.g., blind and remote operations) as a project evolves. Realistic constraints also include command sequencing models, contingency handling, data downlink, and data storage and interpretation.

Field tests and deployments provide valuable lessons-learned opportunities for design improvements, technology needs, and critical operational experience [66]. Ultimately, studies at analogue sites can help to ensure the success of future missions by reducing overall costs and risks during the development and testing phases. By optimizing the choice of instruments and their operating parameters through tests and deployments in analogue environments on Earth, the chances for success of eventual missions is maximized [19,20].

2.2.3. Train

Science investigations and technology validation in analogue environments can serve to train various personnel, from students and educators, to science and mission team members, and ultimately, to astronauts. In fact, various field campaigns featured prominently in the training of Apollo astronauts in the 1960s and early 1970s. Analogue studies provide opportunities for scientists, engineers, educators and students to contribute to the design and planning of missions, by characterizing design and performance of technologies, science approach, and operational concepts, while gaining the operational (hands-on) experience needed for future missions.

Training in tactical operations and the day-to-day (or sol-to-sol) decision-making process can be accomplished through the use of off-site simulated science operations centers (i.e., “backrooms”) [63]. The collection, quality control, validation and interpretation of data can also be developed and practiced during science investigations in analogue environments. It is important to note that mock science investigations or laboratory simulations do not offer the same potential return as actually using the instrument or technology to answer a real science question about the site under investigation. Working in remote, analogue environments thus increases the credibility of the validation and testing when compared to testing in simulated laboratory environments [25]. Lessons learned include, but are not limited to: preferred science operational strategies and command-data sequencing protocols; limitations and impacts of operations; requirements for future development; and issues of human interactions. Such experience and the lessons learned can also help in future team selection and training by demonstrating the specific skills that are required [63].

2.2.4. Engage

Studies in analogue environments are naturally conducive to educational and public outreach (EPO) activities as they easily capture people’s attention because they often take place in remote, exotic locations, and they are directly related to planetary exploration and space missions. EPO activities provide opportunities for the public to participate directly in a space program [9]. Examples of EPO activities in analogue environments include the Spaceward Bound expeditions [41]; the Indiana-Princeton-Tennessee Astrobiology Initiative (IPTAI) “Deep Life” program, including the booklet entitled “Exploring Deep-Subsurface Life. Earth Analogues for Possible Life on Mars: Lessons and Activities” (NASA PRODUCT #EG 2008 03001), and series of classroom lessons on extremophiles and analogue environments; and NASA ASTEP field expeditions, including the AMASE “field blogs”.

2.2.5. Astrobiology-specific functions

More specifically for astrobiology, analogue studies enable the development and validation of biosignatures and detection techniques [11], including establishing baseline abiotic signatures and assessment of biosignature preservation potential and alteration. Analog studies may also potentially lead to the discovery of novel organisms and metabolisms, and the chemical, physical and isotopic imprints of these metabolisms on Mars-like environments. In particular, astrobiology requires the development of biologically relevant, miniaturized instrumentation capable of extensive, autonomous operations on planetary surfaces. In a recently published astrobiology strategy for the exploration of Mars, the National Research Council [44] recommends that studies in analogue sites should include testing of instrumentation, development of techniques for the detection of biosignatures in conditions approaching the martian environment, and technology validation studies.

3. Analogue research and development programs

3.1. CSA Canadian Analogue Research Network (CARN)

In 2005, following recommendations from the scientific community, the Canadian Space Agency (CSA) launched the Canadian Analogue Research Network (CARN). This program includes funding for infrastructure and logistical support at three competitively-selected sites (Haughton-Mars Project Research Station; McGill Arctic Research Station; Pavilion Lake Research Project). In addition, researchers compete annually for research grants in order to perform science investigations or technology validations at the three main CARN sites or at any other analogue field site in Canada, or abroad. CARN addresses requirements for coordination among many field activities and focuses the community on a few field sites, thus helping to build data sets and supporting information [19]. Although not strictly an astrobiology program, roughly two thirds of grants awarded to date have been for investigations with significant components of habitability, extremophiles, biosignatures, planetary protection, or instruments for life detection.

One of the goals of the CARN program is to foster international collaboration. CARN grants have been used to study sites abroad and international collaborators can also receive limited funding to work at Canadian sites with a Canadian-based principal investigator. Related activities include development of a missions database, data archive and web-based geographical information systems (WebGISs) of CARN sites [64]. The CARN program, the only one of its kind, is an integral part of the CSA's strategy for exploration, both with respect to science and technology [31].

3.2. NASA ASTEP

NASA's Astrobiology Science and Technology for Exploring Planets (ASTEP) is a science-driven exploration program that supports science investigations focusing on astrobiological research in terrestrial analogue environments in order to improve knowledge of the limits and constraints on life in extreme environments. ASTEP was conceived to help produce new science and operational/technological capabilities that will enable further planetary exploration. The program aims to decrease the risks of planetary exploration through technology development (i.e., sample acquisition and handling techniques, remote sample manipulation, mobile science systems including planetary rovers, techniques for autonomous operations, and self-contained deployment systems). ASTEP field campaigns [11,60] are conducted with complete systems and in a manner approximating operations on an actual planetary mission. These campaigns contribute to better understanding of the performance, capabilities, and efficiencies of tested systems, while helping team members to gain operational experience.

3.3. Analogue missions

An *analogue mission* is defined by NASA as "an integrated set of activities that will encompass multiple features of the target mission and result in system-level interactions".

Analogue missions are essentially Earth-based expeditions with characteristics that are analogous to missions on the Moon or Mars. Analogue missions investigate solutions to questions related to science definition and requirements of surface missions, test and refine operational concepts and task efficiency; test operations tools; and test design, configuration, and functionality of hardware/software. While analogue and laboratory studies may address what are viable biosignatures and what are the limits of life on Earth (i.e., what is a *habitable environment*), analogue missions act as simulated planetary missions that can provide an opportunity to assess end-to-end system performance and contamination pathways under realistic operational constraints and in a representative environment. Analogue missions thus help to bridge the gap between science goals and the concrete realities of space exploration.

NASA has recently announced an Analogue Missions opportunity, partly in response to the U.S. Congress (Public Law 109-155, section 504), which explicitly instructs NASA to establish ground based analog capabilities in remote locations in the United States in order to develop "lunar operations, life support, and in-situ resource utilization experience and capabilities".

4. Validation of astrobiology technologies and operations in terrestrial analogue environments: case studies

4.1. Haughton-Mars Project Research Station (HPMRS)

The HPMRS is an international multidisciplinary field research project focusing on the Haughton Impact Structure and its surroundings on Devon Island in the Canadian High Arctic (Fig. 1) [37]. The polar desert environment, geological setting (i.e., impact crater), and features (e.g., valleys and gullies, permafrost) make this a site with several characteristics that resemble the Moon and Mars. The geological features (e.g., impact

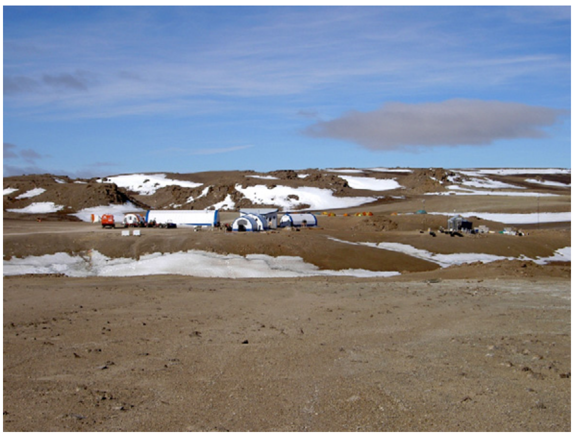

Fig. 1. An example of a terrestrial analogue environment of Mars relevant to astrobiology: the Haughton Impact Structure, Devon Island, Canadian High Arctic. View of the *Haughton-Mars Project Research Station*, located near the western rim of the crater.

Fig. 1. Un exemple d'un environnement analogue terrestre de Mars, important pour l'astrobiologie : le cratère d'impact Haughton, île Devon, Arctique canadien. Vue de la *Haughton-Mars Project Research Station*, située près du contour ouest du cratère.

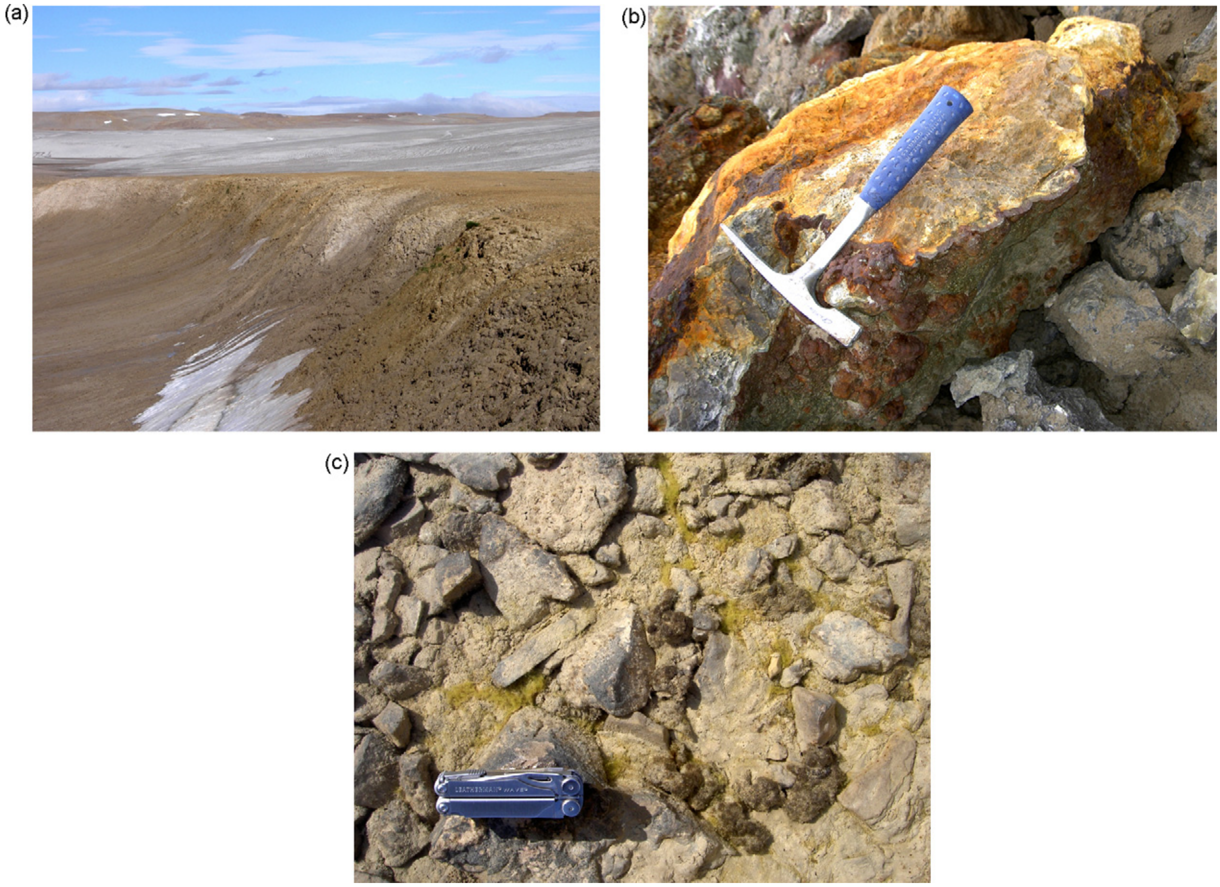

Fig. 2. Astrobiology-related analogue environments at the Haughton Impact Crater, Devon Island, Canada: a: impact breccias (grey, distance) and post-impact, paleolacustrine sediments (beige-brown, foreground); b: sulfide coating from impact-induced hydrothermal systems; c: microbial mats from a dried pond.

Fig. 2. Environnements analogues d'intérêt astrobiologique, situés dans le cratère d'impact Haughton, île Devon, Canada : a : brèches d'impact (gris ; arrière-plan) et sédiments paléolacustres intra-cratère (beige-brun ; premier plan) ; b : couche de dépôts de sulfures hydrothermaux induite par impact ; c : tapis microbiens provenant d'un étang séché.

crater and related deposits) and the biological characteristics (e.g., extremophilic microorganisms, little to no vegetation, uninhabited) are of particular interest to astrobiologists (Fig. 2) [38]. In parallel with various scientific studies, HMPRS supports the development of new technologies for planetary exploration and telecommunications. The project exists since 1997 and is currently managed by the Mars Institute with financial and technical support from the CSA, NASA, and SETI.

In light of NASA's current plan for the exploration of Mars, which has been to *"Follow the water"*, it is widely recognized that it is indispensable to characterize the martian subsurface environment [44]. Several groups are currently developing automated drilling technologies for future Mars missions, and a small (2 m) drill is currently planned for the ESA *ExoMars* rover mission. The project *Drilling Automation for Mars Exploration (DAME)* from NASA Ames seeks to develop an autonomous drilling system capable of drilling into diverse geological materials (rocks, sediments, permafrost, ground ice) that may be encountered on Mars. The HMPRS site was chosen due to the presence of subsurface ice and broken, depth-graded textures, which are expected to be similar to impact regolith, as well as a similar crater morphology [25]. In addition, the remoteness and environment at Haughton also imposed constraints with respect to maintainability and long-term operations in hostile conditions away from sources of readily available software upgrades, tools and electronics upgrades [25]. Tests over several summer field seasons have validated the motor systems, sensors and control software [65]. Over 11 days in 2007, a 3 m deep hole was drilled using a peak maximum power of 150 W. Overall, the field-testing and validation have led to an increase in the level of maturation of drilling automation making it suitable for consideration in future missions [25].

4.2. Arctic Mars Analog Svalbard Expedition (AMASE)

The AMASE program enables the development and validation of scientific instruments in analogue sites in Svalbard (Norway), including instruments that will be aboard the *Mars Science Laboratory* (NASA) and *ExoMars* (ESA) rovers. Specific sites include the Bockfjord volcanic complex, which is characterized by the combination of volcanism, hydrothermal systems and permafrost – all features that are suspected or known to exist on Mars. This location enables the study of interactions between water, rocks and primitive microbial life in an environment that resembles what Mars could have once looked like. The goals of AMASE are to:

- validate the robustness of portable life detection instruments;
- analyze traces of life in Mars analogue environments;
- develop protocols to reduce contamination of instruments and samples [60].

The X-ray diffraction/fluorescence (XRD/XRF) instrument CheMin [52], selected as part of the Mars Science Laboratory (MSL) 2009 mission, was tested during AMASE 2006 and 2007 [3,10]. For the first time, a geological sample was collected, analyzed by XRD, and the results interpreted qualitatively and quantitatively while in the field. The speed at which the analyses and interpretation of results were accomplished demonstrated the feasibility of remotely operating a compact X-ray instrument. On-site XRD/XRF analyses with CheMin enabled a significant improvement in decision-making and efficiency during field studies of complex outcrops [3].

In addition, the Sample Analysis at Mars (SAM) instrument, also selected for MSL, was tested in parallel, in some cases using the same samples as those analysed by CheMin [11]. SAM combines a gas chromatograph/mass spectrometer with a pyrolysis system. Some samples were collected with the prototype robot Teamed Robots for Exploration and Science on Steep Areas, or “Cliffbot” (TRESSA). A field-based cleaning protocol for assuring the sterility of samples collected by the rover was also tested and validated. Field deployment enabled the team to refine analytical protocols, but also coordinate sample preparation, testing, and data interpretation with other instrument teams [11]. The team performed three mock MSL science-operations scenarios that provided valuable training in rover-based planetary science and exploration.

4.3. Rio Tinto basin

The drainage basin of the *Rio Tinto* (“red river”) in southern Spain is characterized by acid conditions caused by the leaching and oxidation of sulfide minerals in the surrounding rocks. The weathering of these sulfide deposits also leads to the formation of secondary mineral deposits similar to alteration minerals identified on Mars [21,22]. In particular, these deposits contain abundant iron oxides/hydroxides and iron sulfates, including jarosite. This site also hosts a unique and diverse subsurface microbial ecosystem, which may be analogous to a subsurface biosphere that once could have existed on Mars [2]. Thus, work on the geomicrobiology of Rio Tinto has led to the formulation of hypotheses about possible relict martian microbial ecosystems, Mars mission concepts, and mission science requirements [2].

The Mars Astrobiology Research and Testing Experiment (MARTE) project was a 3-year NASA-funded project that sought to develop the science and technologies necessary for drilling and sample manipulation for future missions to Mars [13]. In particular, the project included the field demonstration of an integrated semi-autonomous drilling system with drill core processing and life-detection instruments at Rio Tinto. The drilling system used in these field campaigns was able to produce cores in 25 cm lengths and a diameter of 2.7 cm without the use of drilling fluid and operating at or below 150 watts (average) during nominal operations. An automated core handling system removed the acquired core and delivered it to a core clamp for sample preparation and delivery to science instruments. Mission realistic field tests and simulations included interpretation of drill mission results by remote science teams (“blind test”). Cores were analyzed by various imaging systems (panoramic, microscopic, hyperspectral visible/infra red), and the remote science team selected samples for subsampling and more detailed analyses. In some cases, samples were cut and ground before placing in the prototype *Signs Of LIfe Detector* (*SOLID*), an instrument that uses protein microarray technology to detect microorganisms and their metabolic products [49]. This instrument is capable of analyzing several types of biochemical compounds (nucleic acids, proteins, polysaccharides, etc). Several lessons learned have been reported, especially with respect to the drilling activities [13].

4.4. FIDO

NASA's Field Integrated Design and Operations (FIDO) rover is an advanced mobile platform and research prototype for Mars surface missions [53,54]. It is primarily used as a test-and-validation vehicle for technology development under the Mars Technology Program. This has included end-to-end mission concept testing and validation associated with autonomous and semi-autonomous in situ science exploration. The FIDO rover is similar in function and capabilities to the Mars Exploration Rovers. It has been used by the Mars science-and-flight-operations community to conduct field trials aimed at realistic simulation of the Mars Exploration Rovers (MER) mission, including tests in Silver Lake and Soda Mountains, California; Black Rock Summit, Nevada; and Grey Mountain, Arizona [4,53].

In 2002, a 10-day blind test focused on teaching the science team how to remotely conduct field geology using a rover, rather than to test the rover hardware itself. The rover was sent to a distant, undisclosed desert location, while the science team planned the operations and sent commands from a distant location (Jet Propulsion Lab, Pasadena, CA). Mission success criteria, which included going to at least two different locations, making extensive measurements, driving 200 meters (656 feet), and digging a soil trench with one of the rover's wheels, were all met. The latter exercise proved fruitful as the MER *Spirit* was subsequently able to access and analyze subsurface material using such a strategy.

5. Future directions of analogue studies

The first detection of extra-terrestrial biosignatures will raise two important questions: is it a biosignature (i.e., has it been produced by life rather than geochemical processes); and is it real (i.e., are we confidant of the instrument's detection limits given the contamination along the overall pathway of sample acquisition, handling, processing and analysis)? Both of these questions can benefit greatly from extensive analogue studies as shown herein.

The National Research Council (U.S.A.) recommends that terrestrial analogue studies "should continue to be a fundamental aspect of Mars astrobiological research". Continued support of studies in analogue environments is therefore required. Scientific ground-truth measurements are essential for validating current flight instrumentation and for the development of advanced instrumentation and technologies for life-detection missions in the coming years [26]. Analogue missions will continue to focus on similar science and technology development, though at a larger scale than generally seen previously. Larger teams, with more collaboration between scientists, engineers, and operations personnel will be a major asset.

Analogue studies will also be critical for sample return missions, whereby a complex interplay of technologies will be put to use in a very carefully pre-selected site or series of sites on Mars. Analogue studies will be essential for selecting appropriate target sites, sampling and site characterization strategies, and overall mission operations, as well as for developing the multitude of technologies and systems for such a mission.

Recently, an International Analogue Network (IAN) has been proposed [32]. Such a network would facilitate collaborative research and development as well as the exchange of students and postdoctoral researchers. International cooperation in terrestrial analogue environments will act as a catalyst and test-bed for future international space missions. Collaborative analogue studies will also help in the training and integration of international science teams. An International Analogue Working Group is also in its infancy and the 3rd International Workshop on Exploring Mars and its Earth Analogues will be held in Canada in 2009. To maximize the contribution of analogue studies, it will ultimately be necessary to assemble and organize data from various analogue programs and disseminate it to the wider astrobiology and planetary exploration communities.

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