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Résumé de l'article

Les analogues terrestres sont ces endroits sur la Terre qui possède jusqu'à un certain point, les conditions géologiques, environnementales ou biologiques présumées d'un corps céleste, actuelles ou passées. Les études d'analogues terrestres sont nécessaires pour comprendre le fonctionnement de certains processus sur Terre afin de permettre l'interprétation et la validation sur site témoin de données reçues d'orbiteurs non-habités ou de robots mobiles d'exploration. C'est là une occasion idéale d'accentuer la collaboration entre les communautés des sciences planétaires et celles des géosciences au Canada et ailleurs. Les milieux d'analogues constituent aussi des endroits importants permettant d'optimiser les besoins et les stratégies d'exploration de missions habitées vers la lune et Mars. De par ses caractéristiques géographiques et climatiques idéales, sa grande diversité de sites d'analogues, et son histoire d'activités analogues, le Canada est assuré de jouer un rôle de chef de file dans l'utilisation internationale croissante de sites d'analogues terrestres.

ARTICLE

Terrestrial Analogues to Mars and the Moon: Canada's Role

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SUMMARY
Terrestrial analogues are places on Earth that approximate, in some respect, the geological, environmental and putative biological conditions on a particular planetary body, either at the present-day or sometime in the past. Analogue studies are driven by the need to understand processes on Earth in order to interpret and groundtruth data sent back from Mars and other planetary bodies by unmanned orbiters and rovers. This presents an ideal opportunity to further collaboration between the solid earth and planetary science communities in Canada and elsewhere. Analogue environments also provide a critical locale for optimizing exploration requirements and strategies for future manned missions to the Moon and Mars. The ideal geography and climate, a wide diversity of analogues sites, and a history of analogue activities, ensures that Canada can play a leading role in the expanding international use of terrestrial analogues sites.

SOMMAIRE
Les analogues terrestres sont ces endroits sur la Terre qui possède jusqu'à un certain point, les conditions géologiques, environnementales ou biologiques présumées d'un corps céleste, actuelles ou passées. Les études d'analogues terrestres sont nécessaires pour comprendre le fonctionnement de certains processus sur Terre afin de permettre l'interprétation et la validation sur site témoin de données reçues d'orbiteurs non-habités ou de robots mobiles d'exploration. C'est là une occasion idéale d'accentuer la collaboration entre les communautés des sciences planétaires et celles des géosciences au Canada et ailleurs. Les milieux d'analogues constituent aussi des endroits importants permettant d'optimiser les besoins et les stratégies d'exploration de missions habitées vers la lune et Mars. De par ses caractéristiques géographiques et climatiques idéales, sa grande diversité de sites d'analogues, et son histoire d'activités analogues, le Canada est assuré de jouer un rôle de chef de file dans l'utilisation internationale croissante de sites d'analogues terrestres.

INTRODUCTION
In a recent issue of *Geoscience Canada*, Sylvester et al. (2005) presented a summary of discussions regarding the future of Canadian solid earth sciences. As these authors noted, solid earth sciences appear to be at a crossroads in Canada, with the end of LITHOPROBE, the increasing focus on climate change and hydrosphere–atmosphere interactions, and the possible renaming of NSERC Grant Selection Committee 08, as Earth and Planetary Sciences. In particular, recent discussions have highlighted the need to develop strategic partnerships and further collaboration between Canada's solid earth and planetary science communities (Sylvester et al. 2005). At the same time, the world of planetary exploration is rapidly evolving. More than ever before, the international scientific community is attempting to answer fundamental questions concerning planetary evolution and the origins of life by exploring other planets. There are currently more active robotic space missions than at any other time in history. It is clear that humans will return to the Moon in the next 10–15 years and will one day explore Mars, using the Moon as a stepping-stone to demonstrate technologies and to pursue scientific investigations. Mars is of particular importance and interest because it is geologically one of the most earth-like bodies in the Solar System. The Martian crust preserves evidence of a long and varied geological history, with sustained periods of volcanism, tectonism, impact

cratering, and erosion (Kieffer et al. 1992; Head et al. 2001). Even more important, it is the only body in the Solar System, besides Earth, where water is known to have flowed across the surface (e.g. Carr 1996; Masson et al. 2001). This is important because liquid H_2O is a requirement for life, as we know it.

The Moon is the only planetary body, besides the Earth, to have been explored by humans. Currently, the only way to "explore" Mars is *via* data sent back from unmanned orbiting spacecraft and rovers, and through the study of Martian meteorites. However, it is widely recognized that interpretations of Mars must begin by using the Earth as a reference (Farr et al. 2002). This introduces the concept of terrestrial analogues, which are places on Earth that approximate the geological and environmental conditions on Mars and other planetary bodies, either at the present-day or sometime in the past.

Analogue studies are deemed a high priority by the Canadian and international planetary science communities (e.g. Pollard 2001; Farr 2004; Léveillé 2004). Investigation of terrestrial analogues also provides an ideal opportunity to foster collaboration between Canadian and international solid earth science, planetary science, and biological science communities. Under the theme of "Exploring other worlds begins with exploring our own", the Canadian Space Agency (CSA) has established the Canadian Analogue Research Network (CARN) as part of a multi-disciplinary approach to use Mars analogue sites (and those of other planetary bodies), in Canada, to further our scientific understanding of the Solar System, to develop and test specific exploration technologies, and to understand how to explore and live safely on other planets. The aim of this paper is to present an up-to-date review of terrestrial analogues in their many forms, to outline the CSA-led CARN program, and to discuss ways in which the solid earth and planetary science communities can work closer together.

TERRESTRIAL ANALOGUES OF SPACE ENVIRONMENTS

Terrestrial analogues are places or spaces on Earth that approximate, in some respect, the geological, environmental and putative biological conditions and/or setting(s) on a particular planetary body, either at the present-day or sometime in the past. The definition of an analogue is, therefore, necessarily broad: a meteorite impact crater in a polar desert is an obvious analogue for Mars; however, an environmental chamber with the capacity to simulate the atmospheric pressure and chemistry at the surface of Mars is also an equally important analogue "site". Current terrestrial analogue research activities focus on three main areas: 1) comparative planetary geology, including process studies and the characterization of analogue materials; 2) astrobiology; and 3) exploration science, which includes instrument testing and development, astronaut training, and exploration-related activities. Analogue activities also provide important education and public outreach possibilities because they provide a link between current robotic missions and future manned space missions to the Moon and Mars.

Much of the remote, harsh, and often unexplored regions of Canada can serve as analogues for the Moon, Mars, and possibly other planetary bodies. In particular, the Canadian Arctic offers a plethora of potential analogue sites, including vast regions of continuous permafrost, polar deserts, meteorite impact craters, glacial landscapes, perennial springs, ice-covered lakes, and unique biological habitats. It is important to note that by studying the geology and biology of terrestrial analogues, our understanding of other planetary bodies increases. These studies also contribute, often significantly, to our understanding of fundamental scientific problems here on Earth. For example, while a major focus of recent investigations at the Haughton impact structure, Devon Island, Canadian High Arctic, has been to use this site as an analogue for Mars, studies there have also resulted in a substantial increase in our knowledge of polar geology and biology (Cockell et al. 2001, 2003; Lim and Douglas 2003; Parnell et al. 2003; Cockell and Stokes 2004; Eglinton et al. 2005; Osinski and Lee 2005) and impact cratering generally (see Osinski et al. 2005b for a review). As such, analogue studies provide a unique opportunity to foster collaboration between the planetary and solid earth geoscience communities.

COMPARATIVE PLANETARY GEOLOGY

Process Studies

One of the main goals of planetary science is to understand the origin and temporal evolution of landforms and physical features of planetary surfaces, and the relationship of these to the underlying geological structures. Therefore, many aspects of terrestrial analogue studies focus on investigating geological processes that modify the Earth's surface, and extrapolating them to Mars and other planetary bodies (e.g. Figs. 1a–d). Table 1 provides a summary of the main geological processes that modify the Earth's surface, and also shows a comparison with that of the Moon and Mars. Comparisons between certain geological processes, such as basaltic volcanism and extensional tectonics, can be undertaken anywhere on Earth where suitable geology exists (e.g. basaltic volcanism on Hawaii). However, a complete understanding of many geological processes requires research to be carried out at terrestrial sites in environments that are similar to those of other planetary bodies that are known and/or suspected at the present day and in the past. For example, ideal terrestrial analogues to Mars will possess

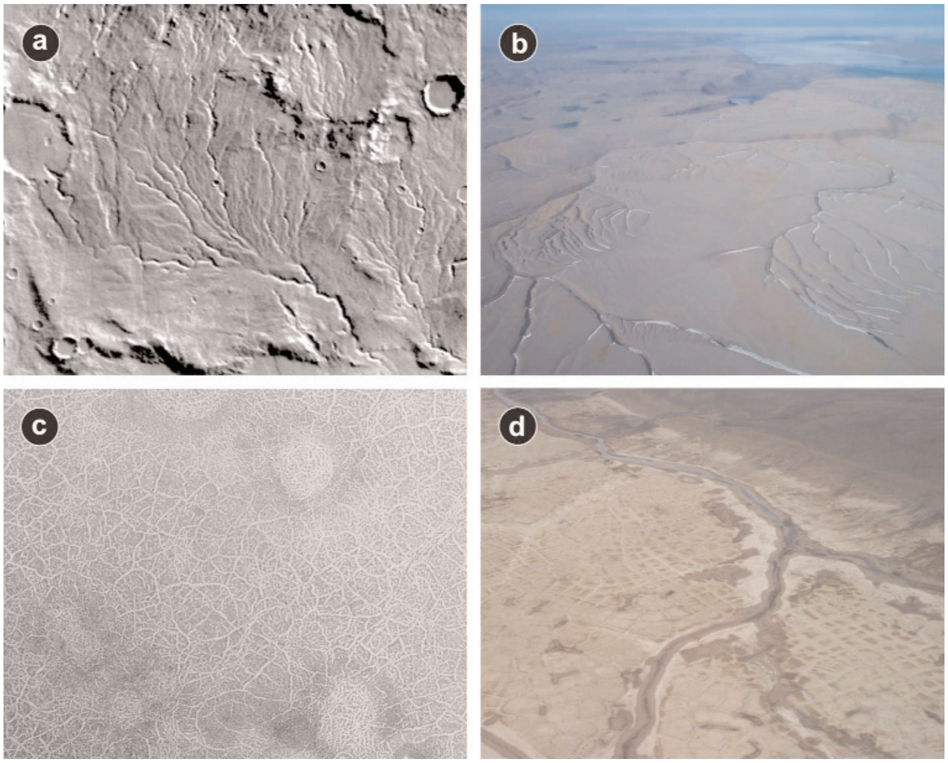

Figure 1. a) Example of a series of valley networks on Mars; image area is ~200 km across. Image credit: Mars Digital Image Map. b) Small valley networks similar to those found on Mars (Fig.1a) are found in the polar desert environment of Devon Island, where they have been interpreted as glacial meltwater channel networks (Lee et al. 1999); image area is ~10 km across. Image: G.R. Osinski. c) Example of Martian polygons, interpreted as periglacial features. Portion of Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) image E09-00029; image area is ~1.5 km across, Image credit: NASA/JPL/Malin Space Science Systems. d) Polygonal terrain in Thomas Lee Inlet, Devon Island, formed as a result of thermal contraction cracking; Image area is ~1 km across. Image: G.R. Osinski.

characteristics including a cold climate and an arid environment, such as in the polar regions of the Earth. As such, the analogue sites are classified in Table 1 according to their "fidelity", which relates to the degree of similarity of a particular analogue site to its counterpart on another planet. Fidelity is considered to be a key element in any analogue activity, particularly exploration-related activities (see below; Snook and Mendell 2004).

It is also notable that there are some important differences between landforms on Mars and possible analogues on Earth so that care must be taken when making comparisons. For example, while Martian channels and valley networks are similar to those found on Earth, there are major differences in terms of size, small-scale morphology, and catchment areas (Figs. 1a, b; Masson et al. 2001). Furthermore, it is important to note that despite similarities in landforms and/or environmental conditions, geological processes can also be unique to a planetary body (e.g. present-day plate tectonics on the Earth).

Investigation of surface processes and comparative studies with other planetary bodies can be carried out using several techniques and methods including, but not limited to, the following: 1) fieldwork and remote-sensing campaigns at terrestrial analogue sites; 2) comparisons between terrestrial and planetary datasets; 3) numerical and computer modelling of geological processes. Terrestrial analogues are also valuable in proof of concept studies. For example, recent studies at the Haughton impact structure have shown that visible-near infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR) spectroscopic and remote-sensing methods can be successfully used to map the impact-exposed subsurface rock types of a terrestrial impact crater and, by analogy, could be used to interpret Martian impact-related features (Tornabene et al. 2005).

Characterization of Analogue Materials

The physical properties (e.g. strength, density, thermal conductivity, etc.) of rocks and minerals affect the efficiency, rate, and outcome of many geological processes. The properties of Martian rocks and minerals are currently investigated using two main methods:

- Laboratory-based studies of the SNC (shergottite, nakhlite, and chassigny) group of meteorites (Nyquist et al. 2001) which number 37 at the time of writing. These are the only known samples from Mars.
- Spectroscopic techniques using remote science instrumentation mounted on orbiting spacecraft (e.g. the Thermal Emission Spectrometer on Mars Global Surveyor), or in-situ instrumentation on rovers and landers (e.g. the Mössbauer Spectrometer and the Alpha Particle X-ray Spectrometer on the Mars Exploration rovers).

Interpretation of spectroscopic data sent back from unmanned orbiters and rovers involves comparisons with spectral libraries of terrestrial rocks and minerals (e.g. Wyatt et al. 2001). Thus, spectra must be collected from a wide variety of terrestrial materials. Recent missions to Mars have begun to demonstrate the planet's near-surface geological diversity. Primary igneous rocks containing olivine, pyroxene, feldspar, ilmenite and magnetite have been identified remotely and in-situ. In addition, sedimentary

Table 1. Summary of the main geological processes that affect the Earth's surface, a comparison with the Moon and Mars, and a summary of relevant analogue sites in Canada.

Process	Earth	Mars	Moon	Examples of associated landforms and/or products	Analogue site(s) in Canada	Fidelity of analogue site [1]	Reference(s)
Aeolian erosion	Y	N	?	Dunes	Athabasca dune field, NT	2	(W. Pollard, pers. comm. 2005)
Chemical sediments	Y	Y	N	Banded Iron Formations	~2.0 Ga Gunflint Formation, ON	1	(Allan et al. 2001)
					~3.8 Ga Porpoise Cove, QC	1	(O'Neil et al. 2006)
Fluvial erosion	Y	Y	N	Valley networks	Devon Island, NU	2	(Lee et al. 1999)
Glacial erosion	Y	Y	N	Erosional channels, deposits	Various locations	N/A	-
Gully erosion	Y	Y	N	Gullies	Devon Island, NU	2	(Lee et al. 2002)
					Axel Heiberg Island, NU	2	(Heldmann et al. 2005)
Hydrothermal activity							
● Volcanic-related	Y	Y	?	Hydrothermal deposits	Mount Edziza, BC	2	(Clark et al. 1989)
● Impact-related	Y	Y	?		Haughton impact structure, NU	2	(Osinski et al. 2005a)
Impact cratering	Y	Y	Y	Impact craters, impact-metamorphosed rocks	Haughton impact structure, NU	1	(Osinski et al. 2005b)
Lacustrine sedimentation	Y	Y	N	Alkaline lakes	Pavilion Lake, BC	1	(Lim et al. 2005)
				Intra-crater paleolakes	Haughton impact structure, NU	2	(Osinski and Lee, 2005)
Shoreline erosion	Y	?	N	Shorelines	Various locations	N/A	-
Mass wasting	Y	Y	Y	Landslides, slumps	Various locations	N/A	-
Perennial spring activity	Y	?	N	Springs, mineralized mounds	Borup Fiord, Ellesmere Island, NU	2	(Grasby et al. 2003)
					Expedition Fiord, Axel Heiberg Is., NU	2	(Andersen et al. 2002)
Periglacial activity	Y	Y	?	Pingos, thermokarst	Tuktoyaktuk Peninsula, NT	2	(Soare et al. 2005)
Rock weathering							
- Physical	Y	Y	Y	Sedimentary deposits	Various locations	N/A	-
- Chemical	Y	Y	N	Secondary minerals	Various locations	N/A	-
Tectonism	Y	Y	?	Faults, folds, etc.	Various locations	N/A	-
Volcanism	Y	Y	Y	Lava flows, pyroclastic deposits, volcanoes	Mount Edziza, BC	2	(Allan et al. 1982)
					Theo's Flow, ON	1	(Lentz et al. 1999)
Volcano–ice interactions	Y	?	N	Sub-glacial volcanoes (Tuyas)	Mount Edziza, BC	2	(Allen et al. 1982)

[1] Fidelity of an analogue site with respect to comparative planetary geology and astrobiology: 1 = the analogue site allows a particular geological and/or biological process to be studied. 2 = the analogue site allows a particular geological and/or biological process in an environment similar to the planetary body in question to be studied

Table 2. Minerals identified on Mars by orbital remote sensing and in-situ rover-based analyses.

Mineral Species	Origin	Detection Method[1]	References
Primary Igneous Minerals			
Olivine Pyroxene (clino- + ortho-) Feldspar (plagioclase, maskelynite) Ilmenite Magnetite	Basaltic rocks; basaltic sands (physically-weathered rocks); soils and dust	MER: Mössbauer, Mini-TES; ME: OMEGA	(Christensen et al. 2004; Bibring et al. 2005; Morris et al. 2006)
Secondary Minerals			
Kieserite Gypsum Polyhydrated sulfates Ca-/Mg-sulphates	Aqueous alteration + deposition	ME: OMEGA; MER: Mini-TES	(Christensen et al. 2004; Gendrin et al. 2005; Langevin et al. 2005; Ming et al. 2006)
Jarosite, Fe^{3+} sulfate	Aqueous/eolian deposition	MER: Mössbauer, Mini-TES, APXS	(Christensen et al. 2004; Klingelhofer et al. 2004; Rieder et al. 2004 Squyres et al. 2004; Morris et al. 2006)
Nanophase ferric oxide	Aqueous alteration + deposition	MER: Mössbauer, Mini-TES	(Ming et al. 2006)
Hematite	Aqueous alteration + deposition	MER: Mössbauer, Mini-TES	(Ming et al. 2006)
Goethite	Aqueous deposition	MER: Mössbauer	(Morris et al. 2006)
Hydrated phyllosilicates (nontronite)	Aqueous alteration	ME: OMEGA	(Bibring et al. 2005)
Aluminosilicates (allophane and amorphous SiO_2)	Aqueous alteration	MGS: TES	(Michalski et al. 2006; Ming et al. 2006)

[1] Abbreviations: ME= Mars Express; MER= Mars Exploration Rovers; MGS= Mars Global Surveyor; Mini-TES= Mini-Thermal Emission Spectrometer; OMEGA= Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité is a visible and near infrared spectrometer; APXS= Alpha Particle X-Ray Spectrometer; TES= Thermal Emission Spectrometer.

rocks and altered igneous rocks containing Fe-oxides, Ca-Mg-Fe-sulfates, and hydrated phyllosilicates (clays) have also been identified (Table 2). In addition to these and the igneous Martian meteorites, many other rocks and minerals are suspected and/or known to be present on the Martian surface or in its interior, including ices and clathrates, carbonates, and other volcanic and magmatic rocks not represented by the SNC meteorites.

Notably, little is known about the spectral signatures of chemically and hydrothermally altered and shock-metamorphosed rocks and minerals; e.g. sulfates have been documented on Mars (Gendrin et al. 2005), although little is known about the spectral properties of shocked sulfates. Much of this analogue work focusing on geological materials will be analytical and laboratory-based; however, suitable samples are required from a variety of field sites. Furthermore, in-situ, field-based studies are also important for ground-truthing data collected from orbit.

ASTROBIOLOGY

Astrobiology is the study of the origins, evolution, distribution, and future of life in the Universe. This discipline addresses basic but fundamental questions (Des Marais and Walter 1999; NASA 2003), such as: 1) How does life begin and evolve? 2) Does life exist elsewhere in the universe?, and 3) What is the future of life on Earth and beyond? As noted by Des Marais and Walter (1999), these questions are interdependent: "an improved understanding of the morphological, chemical, and isotopic traces of early life on Earth (first question) prepares us to analyze samples returned from Mars and elsewhere (second question). Studies of habitable environments and the potential for life beyond Earth (second question) help us chart our future (third question)." Thus, some of the major goals of astrobiology are to understand the origin and evolution of life on Earth, to determine potential habitats for life, and to understand how life survives in extreme environments. Analogue environments provide a key setting to address these fundamental questions about astrobiology. Terrestrial analogue sites inform us about the diversity of habitable environments for life on Earth, and thus aid in the identification of exploration targets of astrobiological interest on other planetary bodies. Terrestrial analogues also inform us on how biological organisms (or their activities) are preserved in the rock record, and in turn help to develop life detection strategies and instrumentation.

EXPLORATION SCIENCE

The human exploration of the Moon and Mars is now in the long-term plans of the U.S. National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Exploration science is motivated by the need to understand and answer fundamental questions about how to explore other planets. For example, how will exploration be conducted and what technologies will be required? How many people will it take? How will the missions be supported from Earth? How will the missions be planned and managed? Exploration science covers a broad range of disciplines and topics and includes, but is not limited to, the following:

- *Psychology and Group Dynamics*. Remote field camps can serve as analogues for future exploration missions in terms of representing some of the human–human interactions that could happen in a space environment. Such factors will be critical for the success of long duration space missions (e.g. Sandal 2001).
- *Instrument and Technology Testing in Analogue Environments*. Field and environmental testing and demonstration are key milestones in the development of any space-borne hardware.
- *Communications and Computing for Planetary Exploration*. This involves the development of personal (i.e. spacesuit), internal base station and/or spacecraft, and interplanetary (i.e. Earth–(Moon)–Mars) communication systems. Point-to-point planetary surface communications are also included in this category.
- *Telemedicine and Operational Space Medicine*. Analogue environments are valuable for testing the concepts, technologies and techniques required to maximize human health, comfort, productivity, and survivability during long duration exploration-class missions.
- *Robot–Human Interactions*. It has been suggested that the optimization of the interaction between humans and robots is one of the most important outstanding questions in planetary exploration (Snook and Mendell 2004). This can only be achieved by deploying robots in the field with scientists conducting science.
- *Mission Control Operations*. The role of Mission Control in long duration lunar and Martian surface missions is unclear, particularly for Mars, where the distances involved will prevent real-time communication. Analogue environments provide an opportunity to improve protocols developed during the Apollo Moon landings in advance of future space missions.
- *Science Operations*. How will astronauts conduct science and explore the surface of the Moon and Mars? What equipment will they need to take with them? Will they require a laboratory, or will sample analysis be left until the return to Earth? These and many other questions remain to be answered before the planned human missions take place.
- *Field Operations, including Training Astronauts*. Analogue sites provide realistic opportunities for advanced astronaut training and for exploring mission concepts, technologies, and techniques.

As noted by Snook and Mendell (2004), the fidelity of an analogue activity is critical. For example, the fidelity required for a technology demonstration, such as a rover, will be dependant on factors such as topography, physical parameters including temperature, precipitation, rock abundance, and the engineering properties of soils and rocks.

ANALOGUE FIELD SITES IN CANADA

The Canadian geography and climate offers a plethora of potential analogue sites. In particular, the polar deserts of the Arctic represent some of the closest analogues to Mars: they are cold, windy, rocky, and in the summer, drenched in ultraviolet radiation (e.g. Lee et al. 1998). The geology of Canada also offers other possible Moon and Mars analogues, such as basaltic volcanoes and anorthosite bodies. Analogue research is currently being carried out at several sites around Canada, as summarized in Table 1. Several specific examples are highlighted below.

Borup Fiord, Ellesmere Island, Nunavut

This location represents a unique occurrence of springs that discharge from the surface of a glacier, precipitating deposits of native sulfur, gypsum and calcite (Fig. 2a; Grasby et al. 2003; Gleeson et al. 2006). The physical and chemical conditions of the spring water and surrounding environment, together with mineralogical and isotopic signatures, suggest that micro-organisms present beneath the ice mediate geochemical reactions and mineral formation (Grasby et al. 2003). This is important in terms of the search for life on Mars where ground-ice is thought to be present over a wide range of latitudes (Feldman et al. 2002) and springs are believed to exist (Andersen et al. 2002). Similar sulfur-rich springs have also been predicted to exist on Europa, and this site is also widely considered to be an analogue of the Jovian satellite (Gleeson et al. 2006).

Figure 2. Field photographs of various analogue sites in Canada. a) Native sulfur at the outlet of a spring on the wall of an incised supraglacial melt-water channel, Borup Fiord, Ellesmere Island, Nunavut. Image: courtesy of S. Grasby. b) Colour Peak springs, Expedition Fiord, Axel Heiberg Island, Nunavut. c) Close-up of the Gypsum Hill springs, Expedition Fiord, Axel Heiberg Island, Nunavut. (Figs. 2b and c, reproduced with permission of D. Andersen from [http://web.mac.com/daleandersen/iWeb/Dale%20Andersen/Welcome.html]. d) Oblique aerial image of the impact melt breccia hills of the Haughton impact structure, Devon Island, Nunavut, showing well-developed gullies and small valley networks. e) Sampling for groundwater geochemistry and gas at seeping borehole at Kidd Creek Mine, Timmins, Ontario. Image: courtesy of B. Sherwood Lollar. (f) Microbialites in Pavilion Lake, British Columbia. Image reproduced with permission of D. Reid. (g) Ibyuk Pingo, Tuktoyaktuk Peninsula, Northwest Territories. Image: courtesy of R. Soare. (h) Archean stromatolite from the Steep Rock Group, Atikokan, Ontario. Image: courtesy of H. Hoffman. i) High-temperature fluid venting from sulfide chimney structures along the Juan de Fuca Ridge. Image credit: Keck-ROPOS.

Expedition Fiord, Axel Heiberg Island, Nunavut

The McGill Arctic Research Station (MARS) was founded in 1959 and is located at 79°26’ N, 90°46’ W, near the termini of the White and Thompson glaciers at the head of Expedition Fiord, western Axel Heiberg Island. Three themes have dominated most of the research projects at Expedition Fiord: permafrost hydrology, extreme environment biology and astrobiology. Of particular interest are the perennial springs, which occur in a region with a mean annual air temperature of –15°C and flow through continuous permafrost 600 m thick (Figs. 2b,c; Pollard et al. 1999). Despite this, the spring maintains constant discharge temperatures of ~6°C and flows throughout the year, which suggests that similar cold springs in continuous permafrost may also occur on Mars (Andersen et al. 2002). Other Martian analogue activities at Expedition Fiord have focused on understanding gully and valley formation (Heldmann et al.

2005), and testing drilling technologies (Briggs et al. 2006). For further details see: [http://www.geog.mcgill.ca/mag2/fieldstations.htm].

Haughton Impact Structure and Surrounding Terrains, Devon Island, Nunavut

The ~39 Ma, 23 km diameter Haughton impact structure is one of the best preserved and best exposed meteorite impact structures on Earth (Fig. 2d; Osinski et al. 2005b). In addition, it is situated in a polar desert environment that is similar in many respects to conditions that may have existed on Mars in the past (Figs. 1b, d; Lee et al. 1998). Investigations at Haughton have been carried out under the auspices of the Haughton–Mars Project [http://www.marsonearth.org/], which is an international, multidisciplinary project. The current research emphasis is in the fields of impact geology (see Osinski et al. 2005b, for an overview), geomorphology, including valley network and gully formation (Lee et al. 1999, 2004), glacial and periglacial geology (Nieto and Stewart 2003), geophysics (Glass et al. 2005), hydrology and limnology (Lim and Douglas 2003), mineralogy and geochemistry of geobiological materials (Léveillé 2006; Parnell et al. 2006), and microbiology (Cockell et al. 2001, 2005). In addition, recent work suggests that the Haughton structure may be an analogue for Martian impact craters that possess so-called "fluidized" or layered ejecta deposits (Osinski 2006). Haughton has also been the focus of substantial exploration science activities, such as instrument and technology testing, communications development, and mission operations planning.

Kidd Creek Mine, Ontario

The deep subsurface has been identified as one of the most promising locations for extant life on Mars (Boston et al. 1992). Although liquid H_2O is unstable on the Martian surface today, saline groundwaters may exist within fractures in the rock deeper in the crust, providing a potential habitat for micro-organisms, methane-producing bacteria, as on Earth (Sherwood Lollar et al. 2006). The Martian subsurface is also considered as a possible source for the methane recently detected in the Martian atmosphere (e.g. Krasnopolsky et al. 2004). Both abiological and biological subsurface processes have been proposed to explain the presence of this methane. There is, therefore, considerable interest in using deep mines on Earth to access potential analogues for the deep Martian subsurface. There are numerous deep mines, both active and inactive, that could potentially benefit our understanding of deep crustal hydrogeological and biogeochemical processes.

The Kidd Creek Mine is situated in 2700 Ma rocks of the Abitibi greenstone belt, which is one of the world's largest massive volcanogenic sulfide deposits. Recent, and ongoing, studies at Kidd Creek have yielded valuable insights into understanding abiogenic versus biogenic sources of methane in the Earth's subsurface (Fig. 2e; Sherwood Lollar et al., 2006). This work may prove to have important implications for understanding the origin of methane on Mars.

Lupin and Ulu Mines, Nunavut

The Lupin and Ulu mines in Nunavut have been the focus of recent investigations by several teams funded by the NASA Astrobiology Institute [http://www.indiana.edu/~deeplife/research.html]. As with the investigations at the Kidd Creek Mine, these activities have focused on understanding microbial communities within the deep subsurface as terrestrial analogues for possible Martian groundwater ecosystems. Given the cold, frozen nature of Mars, microbiological studies of ice and groundwater in the subsurface of the Arctic (and Antarctic) are deemed important (Pratt and Onstott 2006). Recent studies at the Lupin Mine have documented evidence for the occurrence and importance of sulfur cycling and sulfate reducing microbes under suboxic conditions beneath the permafrost (McGown et al. 2006; Pratt and Onstott 2006).

Pavilion Lake, British Columbia

Pavilion Lake is a 5.7 km-long slightly alkaline, groundwater-fed, freshwater lake located in Marble Canyon in the interior of British Columbia, Canada. The Pavilion Lake Research Project (PLRP) is leading analogue studies at this site. It has been suggested that unique microbialite structures within Pavilion Lake are analogues for reef-like structures that may have been present on the Precambrian Earth (Fig. 2f), before the development of coral reefs (Laval et al. 2000). The study of Pavilion Lake and its microbialites will provide useful information on lacustrine water-rock-microbe interactions that could have occurred on Mars. Specifically, understanding the morphogenesis of these structures will help distinguish abiotic from biotic signatures in the rock record, which has important astrobiological implications for the search for life on other planets. For further details of this study, go to: [http://supercritical.civil.ubc.ca/~pavilion/].

Tuktoyaktuk Peninsula, Northwest Territories

The geomorphology of the Tuktoyaktuk Peninsula is dominated by periglacial processes and is host to the greatest concentration of pingos (ice-cored hills) in the world (Fig. 2g; Mackay 1998). Polygon-junction ponds are also common in this region of the Canadian Arctic and are the product of thermokarst processes, which are induced by changes in the thermal equilibrium of ice-rich sediments. Similar landforms have been documented on Mars, particularly in the northern plains such as Utopia Planitia. Based on the geomorphological analogues of the Tuktoyaktuk Peninsula, it has been suggested that periglacial processes are also operating in the northern plains of Mars and that substantial ground-ice may be present (Soare et al. 2006).

Other Potential Analogue Sites in Canada

Precambrian Rock Record and the Canadian Shield

Canada has one of the most extensive Precambrian rock records on Earth, including numerous well-studied micro- and macro-fossil localities (Lucas and St-Onge 1998). This ancient rock record provides a broad array of spatial and temporal scales to study past biology and biosignatures in rocks (Fig. 2h). Of particular importance to astrobiology is that this rock record represents a period of time before plants and animals covered the land surface, and before the evolution of multicellular organisms, and hence represents a 'non-vegetated, microbial planet' analogue of what a microbial world may have resembled on Mars or elsewhere. This allows reconstruction of planetary-scale processes and planetary biotic evolution. Canadian scientists have extensive field experience and geological expertise in dealing with this rock record.

Hydrothermal Systems

Hydrothermal vents or springs are possible analogues of environments on Mars and Europa (Fig. 2i). Canada has some of the best-known and most-studied deep-sea hydrothermal vents off the coast of British Columbia, along the Juan de Fuca and Explorer Ridges (Tivey and Delaney 1986; Tunnicliffe 1986; Pruis and Johnson 2004; Chadwick et al. 2006). Again, Canadian expertise and relative ease of access merits continued development for analogue-related activities. The recently funded cabled observatory NEPTUNE will provide numerous scientific and technological opportunities for studying hydrothermal processes and related phenomena on the Juan de Fuca Ridge, and for the development of novel remote data collection techniques and instruments, which may benefit the planetary exploration community [www.neptunecanada.ca]. A number of terrestrial hot springs are also found in Canada (e.g. Rocky Mountains, Arctic, Vancouver and Queen Charlotte islands).

OTHER ANALOGUE ENVIRONMENTS

A number of laboratory-based analogue environments exist in Canada, such as the hypobaric plant growth chambers at the University of Guelph, the human-rated variable pressure chamber at Simon Fraser University, the Arthur Clarke Mars Greenhouse on Devon Island, Nunavut, and the Mars atmosphere chamber at the University of Winnipeg. These analogue environments provide important complementary opportunities to field-based analogue studies.

THE CANADIAN ANALOGUE RESEARCH NETWORK (CARN)

There is currently a great deal of activity and interest in using terrestrial analogues to further our understanding of Mars. The Canadian planetary science community has deemed analogue studies a high priority area of interest. For example, a recommendation of the 3rd Canadian Space Exploration Workshop was "to establish a network of Arctic–Mars analogue research projects and sites". In addition, one of the main recommendations of the 1st Canadian Astrobiology Workshop was that the "CSA should develop appropriate analogue/astrobiology field sites in Canada and promote astrobiology-related field research" (Léveillé 2004). Analogue studies also provide a unique opportunity to foster collaboration between the planetary and solid earth geoscience communities.

The CSA has, therefore, created the CARN that will enable scientists to carry out field-based analogue research studies anywhere in Canada. This network currently includes three sites chosen (*via* competitive process) to have logistical and infrastructure support (Fig. 3): 1) the Haughton-Mars Project Research Station (HMPRS), Devon Island, Nunavut; 2) the Pavilion Lake Research Project (PLRP) station, British Columbia; and 3) the McGill Arctic Research Station (MARS), Axel Heiberg Island, Nunavut. In addition, the Exploration Systems Operations Centre (ExSOC) based at Simon Fraser University, British Columbia, was selected to provide engineering, communications, and safety support, and mission operations support, analysis, management, and planning services for analogue activities at these (and other) sites. The CSA has also recently awarded several research grants to Canadian researchers to undertake field-based studies at these and other sites, in the first round of its annual CARN Request for Proposals. It is anticipated that, in future years, investigations at these sites will continue and that several other, as yet unidentified sites, will be chosen and incorporated into the CARN. The main goals of the CARN are to:

- Establish a coordinated network of Moon–Mars–Icy moon analogue sites in Canada.
- Enable scientists to carry out field-based analogue and exploration-related research studies in the Arctic and elsewhere in Canada.
- Enhance the use of space-borne and airborne remote sensing datasets in analogue studies.
- Foster collaboration between the CSA, other Canadian government departments (e.g. Natural Resources Canada), universities, industry, and international partners.
- Increase the competitiveness of Canadian scientists in the few opportunities that exist for participation in planetary missions.
- Provide field laboratories to test technology of use to industry and northern communities.
- Enhance the use and enable

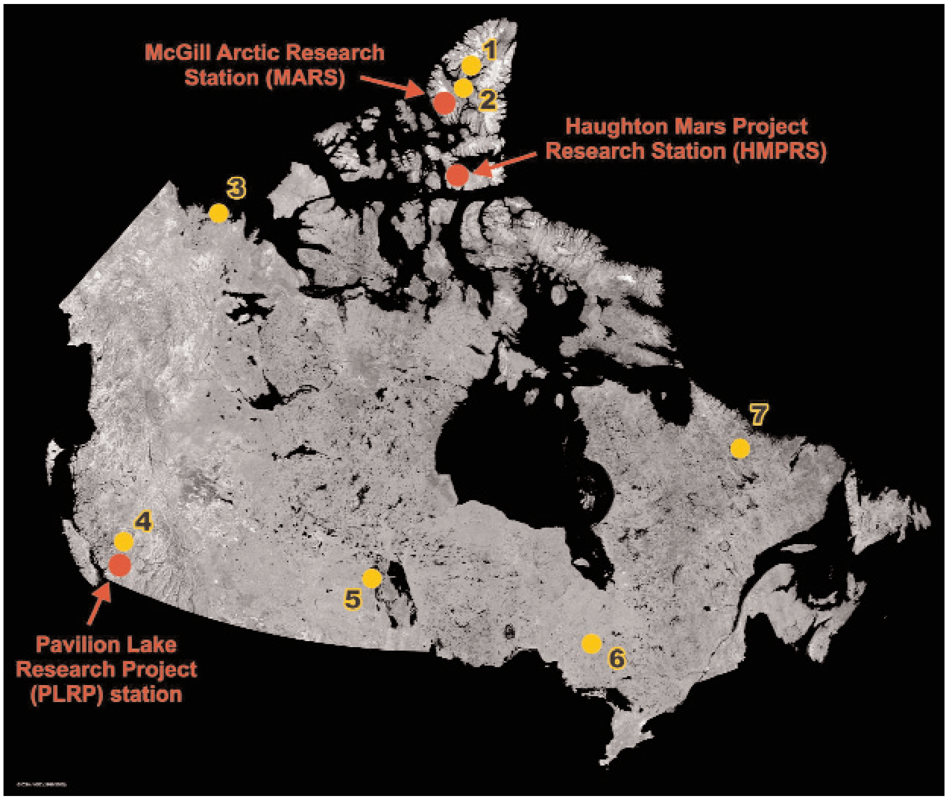

Figure 3. Current activities of the Canadian Analogue Research Network (CARN) superimposed on a Radarsat mosaic of Canada. The red dots represent the 3 sites chosen (*via* competitive process) to have logistical and infrastructure support. The yellow represent sites in Canada where analogue studies have been funded by the Canadian Space Agency. 1 = Borup Fiord, Ellesmere Island, Nunavut. 2 = Eureka Sound lowlands, Ellesmere Island, Nunavut. 3 = Tuktoyaktuk Peninsula, Northwest Territories. 4 = Various evaporite basins, British Columbia. 5 = East German Creek, Manitoba. 6 = Kidd Creek Mine, Ontario. 7 = Mistastin impact structure, Newfoundland and Labrador.

greater access of the Canadian Arctic by the scientific community.

Terrestrial analogue studies are also underway elsewhere in the world (see Farr et al. 2002, for a review); however, as noted by Farr (2004), there is currently little or no coordination between the many individual projects. As part of a U.S. National Research Council decadal community report, Farr (2004) made several recommendations:

1) Coordinated deployment of airborne, space-borne, field instrumentation, and personnel to several sites should be undertaken to test instruments and technology intended for Mars and to provide data for ongoing studies of terrestrial geologic processes relevant to Mars.
2) Collect, document, and make available *via* the internet existing archives of terrestrial data relevant to Mars studies.
3) Support of a series of process-oriented workshops for established scientists, graduate students, and scientist-astronauts.
4) Characterize more fully various Mars analogue materials.

Although the CARN will address many of these issues, cooperation and coordination at the international level is essential to enact all of these recommendations. Canada is ideally suited to act as a leader in this endeavour and serve as a focal point for analogue studies for several reasons, including the ideal geography and climate, the wide diversity of analogue sites, and a history of analogue activities, including exploration science. In addition, unlike parts of Antarctica, which have some of the best analogue field sites on Earth, field sites in Canada are relatively easy to access, particularly as a result of a pre-existing logistical framework (e.g. the Natural Resources Canada Polar Continental Shelf Project) and, now, the Canadian Space Agency's CARN program. Large regions of Canada are still being actively explored; some of this exploration can be driven by the planetary science community. To highlight and promote much of this work, a special session on Terrestrial analogues will be offered at the 2007 Geological Association of Canada–Mineralogical Association of Canada Annual Meeting, in Yellowknife. In cooperation, much essential experience and useful information can be transferred from the solid earth to the planetary science community. Ultimately, such efforts will bring the scientific community closer to achieving its goals of understanding the Earth and its neighbours.

FUTURE DIRECTIONS

It is a desire of the CSA to continue to expand the CARN to more sites throughout Canada, and to create links to key partners with the goal of making this effort more international. Joint planning has already begun with the Italian Space Agency, with a workshop on terrestrial analogues planned for mid-2007 [http://irsps.sci.unich.it/education/mars07/]. Eventually, holding workshops and exploration meetings at Canadian analogue sites would be envisaged. A true international network will make available any site to any researcher in a participating country, for the benefit of the entire planetary science and exploration communities. The CSA is uniquely positioned to offer training in the areas of planetary geology and astrobiology, including field schools, specifically aimed at international crews and their support cadre.

CARN will bring together expertise to implement robotic and manned mission simulations, for demonstration of end-to-end solutions, increasing experience where it needs to be developed. It will make Canadian scientists more internationally competitive for those few mission opportunities that occasionally present themselves. As future Moon–Mars missions will likely be highly international, participating nations and astronaut training programs could benefit significantly by the formation of an International Analogue Network. This network would increase exploration initiative visibility in the member states and improve astronaut field training, in terms of site infrastructure and diversity over the multi-nation sites used during the Apollo program. Thus, it is envisaged that CARN will become a galvanizing force for the exploration community, bringing together scientists, engineers, space operation specialists, crew trainers, and the outreach community.

Finally, a key goal of CARN is to encourage collaboration between earth and planetary scientists to maximize Canadian and international expertise in relevant fields. This was one of the recommendations made by Sylvester et al. (2005) following discussions about the future of Canadian solid earth sciences. In addition to participation in CARN, other possible means for fostering collaboration between earth and planetary scientists include organizing special sessions on planetary science-related subjects at national and international conferences (e.g. a special session is planned on "Comparative planetary geology: Terrestrial analogues to Mars and the Moon in the Arctic" at GAC–MAC 2007 in Yellowknife), establishing a Planetary Geology Division of the Geological Association of Canada, and increasing the scope and awareness of planetary science programs in Earth Science departments in Canadian universities. Together, earth scientists and space scientists will cooperate, to benefit our knowledge of the Earth, while preparing us for the exploration of the solar system.

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