



Geological repositories: scientific priorities and potential high-technology transfer from the space and physics sectors

SUSANA O. L. DIREITO¹, SAMANTHA CLARK², CLAIRE COUSINS¹, YOSHIKO FUJITA³, JON GLUYAS², SIMON HARLEY⁴, RICHARD J. HOLMES⁵, IAN B. HUTCHINSON⁶, VITALY A. KUDRYAVTSEV⁵, JON LLOYD⁷, IAN G. MAIN⁴, MARK NAYLOR⁴, SAM PAYLER¹, NICK SMITH^{8,9}, NEIL J.C. SPOONER⁵, SAM TELFER⁵, LEE F. THOMPSON⁵, KATINKA WOUTERS¹⁰, JOANNA WRAGG¹¹ AND CHARLES COCKELL^{1,*}

- ¹ UK Centre for Astrobiology, SUPA, School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, Midlothian, Scotland
- ² Department of Earth Sciences, Centre for Research into Earth Energy Systems, Durham University, Durham DH1 3LE, UK
- ³ Nano-Science Center, Department of Chemistry, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark
- ⁴ School of GeoSciences, University of Edinburgh, Edinburgh, EH9 3JW, Scotland
- ⁵ Department of Physics and Astronomy, The University of Sheffield, Houndsfield Road, Sheffield S3 7RH, UK
- ⁶ Space Research Centre, Department of Physics & Astronomy, University of Leicester, Leicester LE1 7RH, UK
- ⁷ School of Earth, Atmospheric and Environmental Sciences, The University of Manchester, Oxford Road, Manchester M13 9PL, UK
- ⁸ School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Oxford Road, Manchester M13 9PL, UK
- ⁹ National Nuclear Laboratory, Chadwick House, Birchwood Park, Warrington WA3 6AE, UK
- ¹⁰ Microbiology Unit, Institute for Environment, Health and Safety, Belgian Nuclear Research Centre SCK•CEN, Mol, Belgium
- ¹¹ British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK

ABSTRACT

The use of underground geological repositories, such as in radioactive waste disposal (RWD) and in carbon capture (widely known as Carbon Capture and Storage; CCS), constitutes a key environmental priority for the 21st century. Based on the identification of key scientific questions relating to the geophysics, geochemistry and geobiology of geodisposal of wastes, this paper describes the possibility of technology transfer from high-technology areas of the space exploration sector, including astrobiology, planetary sciences, astronomy, and also particle and nuclear physics, into geodisposal. Synergies exist between high technology used in the space sector and in the characterization of underground environments such as repositories, because of common objectives with respect to instrument miniaturization, low power requirements, durability under extreme conditions (in temperature and mechanical loads) and operation in remote or otherwise difficult to access environments.

KEYWORDS: carbon dioxide, CCS (Carbon Capture and Storage), climate change mitigation, geological disposal, geological repositories, radioactive waste disposal (RWD), space sector, technology transfer.

* E-mail: C.S.Cockell@ed.ac.uk
DOI: 10.1180/minmag.2015.079.6.41



The publication of this research has been funded by the European Union's European Atomic Energy Community's (Euratom) Seventh Framework programme FP7 (2007–2013) under grant agreements n°249396, SeclGD, and n°323260, SeclGD2.

Introduction

THE disposal of radioactive waste from nuclear applications (e.g. from the nuclear power industry, nuclear weapons, medical applications and research programs) is currently an environmental concern worldwide. According to the International Atomic Energy Agency's (IAEA) 2007 report, the worldwide amount of spent fuel mass (of heavy metal) is $\sim 18 \times 10^7$ kg and 1×10^7 kg are produced per year (International Atomic Energy Agency, 2007). The leading option to address this problem is the construction of long-term (i.e. over tens of thousands of years) subsurface geological repositories for the management of these wastes (Long and Ewing, 2004). According to the glossary of the U.S. Nuclear Regulatory Commission (NRC), the definition of a geological repository is: "An excavated, underground facility that is designed, constructed, and operated for safe and secure permanent disposal of high-level radioactive waste. A geological repository uses an engineered barrier system and a portion of the site's natural geology, hydrology, and geochemical systems to isolate the radioactivity of the waste" (NUREG-1350, 2013). For radioactive waste disposal (RWD), a multiple barrier approach is preferable given the difficulty in predicting the performance of a geological repository over very long time frames (Toth, 2011), and it is critical that the engineered barriers work together with the natural environment for isolation and containment (Vines and Beard, 2012).

Another class of geological repositories are those which are intended to safely and effectively store carbon dioxide (CO₂) gas (Carbon Capture and Storage; CCS). CCS repositories can be located in depleted gas fields (Jenkins *et al.*, 2012), depleted hydrocarbon fields, deep saline aquifers and coal seams (Rütters and CGS Europe partners, 2013). However, repositories can also be located away from potential resources and therefore they are less well characterized. Depleted oil and gas reservoirs have an estimated storage capacity of ~ 675 – 900 GtCO₂ (gigatonnes of CO₂), deep saline formations ~ 1000 GtCO₂ or an order of magnitude higher and uneconomical coal formations ~ 3 – 200 GtCO₂ (Benson and Cook, 2005). These are globally significant amounts of CO₂, and highlight the potentially important role of geological repositories in addressing one of the major environmental challenges of the 21st Century: climate change.

Burying waste far from populated areas (although this is often not possible), the biosphere,

the atmosphere and the hydrosphere in the deep underground, confined by geological substrates/strata/formations is thus currently the favoured approach (Long and Ewing, 2004; Toth, 2011). There are a number of challenges to be addressed that relate to the physical, geochemical and biological processes that might occur in repository sites worldwide. These challenges apply to either or both RWD and CCS, and any other use of the subsurface for geodisposal. In order to evaluate plans for geological disposal of different types of waste, and to gather sufficient information to make the case compelling, it is necessary that the geophysical, geochemical and geobiological processes that occur within the subsurface, and that might influence the long-term fate of the waste are understood thoroughly.

One of the important challenges is to identify technology transfer areas that could facilitate geological repository site selection, construction and monitoring. Many of the problems faced in building and maintaining such facilities have similarities to technology requirements in studying the physics, chemistry and biology of any extreme environment, and in particular environments encountered during space exploration.

Repository monitoring is one need, which could potentially benefit significantly from technology transfer. Monitoring could provide relevant information during all stages of repository development and maintenance, including during: (1) surface exploration of the repository site; (2) access just prior to construction or exploratory drilling and underground exploration; (3) construction or expansion of the repository; (4) emplacement (for RWD) or injection (for CCS) of the waste; (5) disposal tunnel backfilling (for RWD) or injection well plugging (for CCS); (6) backfilling and the sealing of the repository; and possibly (7) the long post-closure period. In the case of RWD, monitoring is required to ensure the stability of nuclear safeguards. The European Commission has funded a collaborative project (MoDeRn – Monitoring Developments for safe Repository operation and staged closure; Solente *et al.*, 2013), for developing and possibly implementing monitoring activities during relevant phases of the RWD process (site characterization, construction, operation and staged closure, and post-closure control phase). Therefore, it is timely to review the potentially promising areas of technology transfer from space exploration and particle and nuclear physics sectors.

Science priorities and technology transfer opportunities

The establishment of geological repositories is a huge area in which a vast concentration of research and technology development has occurred (e.g. Benson and Cook, 2005; Birkholzer *et al.*, 2012; Scott *et al.*, 2013). In order to evaluate how technologies developed for the space sector can advance the scientific understanding needed for geological repository siting and operation, it is first necessary to identify some of the key science questions that need to be answered. This paper does not attempt to provide an exhaustive list of science questions, but instead identifies some of the high priority areas in geological disposal that could benefit from tools and approaches developed in high-technology areas such as the space sector. Science questions under the themes of geophysics, geochemistry and geobiology are reviewed, and potential technology transfer options are considered, noting that many of them could promote scientific advances under all three themes. These science areas and their potential for technology transfer were identified by GeoRepNet (Geological Repositories Network), a three year UK Science and Technology Facilities Council (STFC) network set up to investigate potential high-technology transfer into geological repositories.

The focus of this paper is on technologies that can be transferred from the particle and nuclear physics sector and, in particular, from the space sector to tackle the prioritized science questions (Table 1). Space instrument engineers are dedicated to a number of specific aims in instrument development including miniaturization, low energy requirements, long-term operation and operation under extreme conditions and in difficult to access locations (e.g. on the surfaces of other planetary bodies). Similar conditions and constraints are encountered in geological repository environments and thus it seems likely that some of these technologies and instrument strategies could be adapted with appropriate modifications, for use in the monitoring of geological repositories during construction and post-closure.

There are also a range of facilities, such as synchrotron sources and deep underground laboratories that could potentially play a role in testing technology transfer in all three areas discussed. The access to deep subsurface environments, such as underground laboratories, offers the potential to test technology appropriate for both planetary exploration/high-technology physics and geological

repositories in environments where synergies between both applications can be developed.

Geophysics

Robust knowledge of the geophysical and/or of the geomechanical context of a repository site is essential to understanding mechanical, hydraulic, thermal and other physical processes (e.g. formation and propagation of fractures, temperature-induced effects in relation to heat-generating waste, swelling/sealing of clays) and other related facets like geochemistry and geobiology. Indeed, the geochemistry of a repository site and the way in which the chemistry interacts with the subsurface biota are constrained by the physical characteristics of the environment. Key questions specific to geological repository siting and monitoring include:

(1) *How can we accurately understand and monitor stress fields, before, during and after repository construction?* This work is important for understanding how the geological repository environment will evolve over time and potentially identifying, and even forecasting, points of weakness. Examples of techniques currently used in carbon capture include the measurement of subsurface pressure, time-lapse 3D seismic imaging, vertical seismic profiling and crosswell seismic imaging, passive seismic monitoring, land surface deformation using interferometry and GPS, visible and infrared imaging from satellite or planes (Benson and Cook, 2005). Most of these techniques require periodic mobilization of resources for repeat surveys. Such episodic surveys conducted over time scales of tens of years are expensive (especially on-shore seismic surveys) and their results are affected by environmental conditions not necessarily linked to the monitored parameters.

(2) *Have we identified and understood the uncertainties and do we have confidence in the results?* Mapping subsurface geology and its geophysical/geomechanical properties has inherent uncertainties. Characterizing these uncertainties is essential to predicting the behaviour of a repository, particularly in the long-term post-closure and yet carrying out this characterization of uncertainties remains in its infancy. The level of uncertainty varies between different locations, classes and type of repository (RWD or CCS), for example there is only limited experience in identifying and locating sites suitable for CCS beyond the regional scale (e.g. for saline aquifers) (Wilkinson *et al.*, 2013).

TABLE 1. Major technology challenges on geological repositories and possible technology transfer from space technology, missions and other physics areas.

Major technical challenge (number in text)	Instrument/ Mission/ Space Agency	Mission status	Description of instrument(s)	References	Technology reports/ Official webpages
Geophysics (1) Monitoring of stress fields/ Seismic monitoring	SEIS seismic instrument/ InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) lander/ NASA	In development (planned launch: March 2016)	InSight will carry three instruments in order to explore Mars' interior: its internal seismic activity (SEIS seismic instrument), geothermal heat (HP3 heat-flow and physical properties probe) and rotational variations (RISE X-band radio Doppler tracking experiment). Will demonstrate communications and navigation technologies directed at supporting future missions and will place four one-metre-long penetrators into the lunar surface in order to establish a global network of seismometers, heat flow sensors and volatile detectors to investigate the seismic environment and interior of the Moon.	Trebi-Ollennu <i>et al.</i> (2013) Davies <i>et al.</i> (2007); Gao <i>et al.</i> (2008)	http://insight.jpl.nasa.gov/docs/InSight_NASA_fact_sheet_rev3_June_2013_FC.pdf
(2) Mapping subsurface geology and its geophysical properties	MoonLITE (Moon Lightweight Interior and Telecoms Experiment) orbiter/ UK Space Agency	In development			
	CheMin – Chemistry and Mineralogy instrument/ Mars Science Laboratory (MSL) Curiosity rover/ NASA	Current mission (launched: Nov., 2011)	Comprises a powder X-ray diffraction (XRD) and an X-ray fluorescence (XRF) instrument in order to determine the mineralogical and chemical composition of Martian rocks and soils.	Blake <i>et al.</i> (2012); Zimmerman <i>et al.</i> (2013)	http://msl-seicorner.jpl.nasa.gov/Instruments/CheMin/
	Raman Laser Spectrometer (RLS)/ ExoMars rover/ ESA and Roscosmos	Future mission (planned launch: 2018)	A compact Raman spectrometer that will perform Raman spectroscopy on crushed powdered samples inside the rover in order to establish mineralogical composition and identify organic pigments.	Edwards <i>et al.</i> (2012); Lopez-Reyes <i>et al.</i> (2013)	http://exploration.esa.int/mars/45103-rover-instruments/?body/longid=2130
	MARSIS – Mars Advanced Radar for Subsurface and Ionosphere Sounding instrument/ Mars Express orbiter/ ESA	Past mission (launched: June 2003)	A subsurface radar sounder with a 40 m antenna which has been collecting data from the subsurface with the aim of searching for water. MARSIS provided strong evidence for a former ocean on Mars.	Mouginot <i>et al.</i> (2012)	On Mars Express: www.esa.int/esapub/sp/sp1240/sp1240web.pdf

<p>WISDOM – Water Ice and Subsurface Deposit Observation On Mars instrument/ ExoMars rover/ ESA and Roscosmos</p>	<p>Future mission (planned launch: 2018)</p>	<p>An UHF (frequency range from 500 MHz to 3 GHz) ground-penetrating radar to characterize the stratigraphy under the rover and to be used in combination with Adron; this can provide information on subsurface water content, to choose where to collect subsurface samples. Detectors of cosmic-ray muons capable of measuring muon angular distribution beneath a geological repository and compare it with predictions. Long-term measurements would allow us to monitor changes in density profile above the muon detector.</p>	<p>Ciarletti <i>et al.</i> (2011) http://exploration.esa.int/mars/45103-rover-instruments/?fbody/longid=2128</p>
<p>Muon tomography</p>	<p>First tests for geological repository monitoring are in progress</p>	<p>Has two complementary operational modes: Gas Chromatograph–Mass Spectrometry (GC–MS) to identify and analyse volatile molecules and Laser Desorption–Mass Spectrometry (LD–MS) to analyse less volatile molecules and heat-resistant materials.</p>	<p>Kudryavtsev <i>et al.</i> (2012) https://www.dur.ac.uk/dei/projects/muon/</p>
<p>(3) Movement, transport and speciation of gases</p>	<p>Future mission (planned launch: 2018)</p>	<p>MOMA – Mars Organics Molecule Analyser instrument/ ExoMars rover/ ESA and Roscosmos</p>	<p>Evans-Nguyen <i>et al.</i> (2008); Brinckerhoff <i>et al.</i> (2013) http://exploration.esa.int/mars/45103-rover-instruments/?fbody/longid=2132</p>
<p>Modulus Ptolemy instrument/ Rosetta lander/ ESA</p>	<p>Current mission (launched 2004)</p>	<p>Analysed instrument on board Rosetta (ESA mission to characterize the comet 67 P/ Churyumov-Gerasimenko) includes a miniaturized GC/MS system with an ion trap mass spectrometer particularly developed for isotope ratio measurements of solid and volatile materials.</p>	<p>Todd <i>et al.</i> (2007) http://sci.esa.int/rosetta/47366-fact-sheet/</p>
<p>SAM – Sample Analysis at Mars instrument/ Mars Science Laboratory (MSL) Curiosity rover/ NASA</p>	<p>Current mission (launched: Nov., 2011)</p>	<p>Comprises a set of three instruments: a gas chromatograph, a quadrupole mass spectrometer and a tunable laser spectrometer, in order to look for and measure the abundances of carbon, oxygen, hydrogen and nitrogen elements associated with life.</p>	<p>Atreya <i>et al.</i> (2013); Leshin <i>et al.</i> (2013); Ming <i>et al.</i> (2014); Wong <i>et al.</i> (2013) On MSL: http://marsprogram.jpl.nasa.gov/msl/news/pdfs/MSL_Fact_Sheet.pdf</p>

(continued)

TABLE 1. (contd.)

Major technical challenge (number in text)	Instrument/ Mission/ Space Agency	Mission status	Description of instrument(s)	References	Technology reports/ Official webpages
	LADÉE (Lunar Atmosphere and Dust Environment Explorer) lander/ NASA	Ongoing mission, on science analysis stage after a controlled impact on the lunar surface (launched: Sept. 6, 2013).	To collect detailed information on the conditions near the lunar surface, atmosphere and environmental influences on lunar dust. Onboard: Ultraviolet and Visible Light Spectrometer (to determine the composition of the lunar atmosphere), Neutral Mass Spectrometer (to measure variations in the lunar atmosphere over several lunar orbits), Lunar Dust Experiment (to collect and analyse samples of lunar dust) and Lunar Laser Communications Demonstration (for technology demonstration).	Stubbs <i>et al.</i> (2010); Sarantos <i>et al.</i> (2012); Lakdawalla (2013)	http://www.nasa.gov/sites/default/files/ladee-fact-sheet-20130129.pdf
Geochemistry (1) Mapping/ Monitoring of chemical processes for modelling	CLUPI – CLose-UP Imager/ ExoMars rover/ ESA and Roscosmos	Future mission: Exomars, (planned launch: 2018)	A miniaturized camera system that will acquire high-resolution colour close-up images of rocks, outcrops, drill fines and drill core samples from 2 metres depth. Stereo, multispectral wide angle and high-resolution camera which will provide contextual geological data through (1) digital terrain mapping of the Martian surface by capturing wide angle stereo imagery, (2) acquiring multispectral (440–1000 nm) images for the identification of mineralogically-distinct units and (3) acquiring high-resolution images of distant targets. It is comprised of two Wide Angle Cameras (WACs) and one High-Resolution Camera (HRC).	Josset <i>et al.</i> (2012)	http://www.space-x.eu/index.php?option=com_content&view=article&id=116&Itemid=56
	PanCam - Panoramic Camera/ ExoMars rover/ ESA and Roscosmos	Future mission: Exomars, (planned launch: 2018)		Coates <i>et al.</i> (2012); Cousins <i>et al.</i> (2012); Yuen <i>et al.</i> (2013)	http://exploration.esa.int/mars/45103-rover-instruments/?body/longid=2127
(2) Effects of impurities on geochemistry	MoonLITE* SAM*	See above See above	See above See above	See above See above	See above See above

<p>(3,4) Detection of leakage of CO₂, radionuclides and other gases that could be indicative of subsurface repository change or leakage</p>	<p>Mars chamber simulating CO₂ atmosphere and other simulation chambers</p> <p>TGO – Trace Gas Orbiter instrument/ ExoMars/ ESA and Roscosmos</p>	<p>Ground based</p> <p>Future mission: Exomars, (planned launch, 2016)</p>	<p>Different kinds of Mars-simulating chambers have been built over the years in order to simulate Mars surface conditions.</p> <p>To detect methane and other atmospheric gases that are present in small atmospheric concentrations (<1% on Mars. Includes the ACS (Atmospheric Chemistry Suite) which is a set of three spectrometers, covering a total range of 0.7–17 µm.</p>	<p>de Vera <i>et al.</i> (2014); Sobrado <i>et al.</i> (2014)</p> <p>Korablev <i>et al.</i> (2013)</p>	<p>—</p> <p>http://exploration.esa.int/mars/46475-trace-gas-orbiter/</p>
<p>Geobiology</p>	<p>SOLID – Signs Of Life Detector/ Icebreaker Life Lander/ NASA</p>	<p>See above</p> <p>See above</p> <p>See above</p> <p>Future mission (launch: 2018)</p>	<p>An antibody microarray-based instrument capable of including up to 500 different antibodies for the detection and identification of microbes and biological compounds (e.g. proteins, polysaccharides, nucleic acids) by <i>in situ</i> analysis of solid (soil, sediments, crushed rocks or ice) and liquid samples. SOLID version 3.1 is a portable field instrument.</p>	<p>See above</p> <p>See above</p> <p>See above</p> <p>Parro <i>et al.</i> (2005); Stoker <i>et al.</i> (2008); Parro <i>et al.</i> (2011)</p>	<p>—</p>
<p>(1) Knowledge on subsurface microbial communities</p>	<p>LMC – Life Marker Chip, withdrawn from ExoMars rover/ ESA and Roscosmos</p>	<p>Potential for future life detection missions</p>	<p>Microfluidic antibody- based instrument that uses surfactant-based solvents to extract organic compounds from samples of soil or crushed rock and to transfer the extracts to the detectors.</p>	<p>Sims <i>et al.</i> (2012); Septon <i>et al.</i> (2013)</p>	<p>http://robots.open.ac.uk/space/LMC.html</p>
<p>(2) Better understanding of the disturbance on the ecology of deep repositories</p>	<p>Raman Laser Spectrometer (RLS)*</p>	<p>See above</p>	<p>See above</p>	<p>See above</p>	<p>See above</p>
<p>(3) Gases generated by microbial metabolisms</p>	<p>SAM*</p> <p>SAM*</p> <p>TGO – Trace Gas Orbiter instrument*</p>	<p>See above</p> <p>See above</p> <p>See above</p>	<p>See above</p> <p>See above</p> <p>See above</p>	<p>See above</p> <p>See above</p> <p>See above</p>	<p>See above</p> <p>See above</p> <p>See above</p>

(continued)

TABLE 1. (contd.)

Major technical challenge (number in text)	Instrument/ Mission/ Space Agency	Mission status	Description of instrument(s)	References	Technology reports/ Official webpages
(6) Finding analogue environments	—	—	Terrestrial analogue studies support most planetary missions and their use is essential for exploratory missions. In the same way, analogue environments that in some way approximate to the geological repository environment should be considered.	Preston and Dartnell (2014); Fairén <i>et al.</i> (2010)	—
General monitoring Automatic sampling/ Robotics	Icebreaker Life Lander/ Mars Icebreaker Life Mission/ NASA	Future mission (launch: 2018)	It will search for life in ice-rich regions on Mars carrying life-detection instruments, 0.5–5 m automated rotary and rotary-percussive drills (tested successfully in analogue field sites and Mars chambers and to 1–3 m depths) and a triple redundant sample delivery system.	Dave <i>et al.</i> (2013); McKay <i>et al.</i> (2013); Zacy <i>et al.</i> (2013); Glass <i>et al.</i> (2014)	—
Radiation monitoring	Radiation Assessment Detector instrument (RAD)/ Curiosity Rover/ NASA	Current mission (launched: Nov., 2011)	It is one of the first instruments sent to Mars in preparation for future human exploratory missions. Capable of measuring all high-energy radiation on Mars' surface (e.g. protons, energetic ions, neutrons and gamma rays).	Ehresmann <i>et al.</i> (2014)	http://mars.jpl.nasa.gov/nsl/mission/instruments/radiationdetectors/rad/
	Gamma-ray and neutron detectors, radon measurements	Extensive R&D efforts	Work on improvements of detection efficiency for gamma-rays and neutrons at 0.1–10 MeV energies, typical for radioactivity. Development of new neutron detectors that do not use very expensive and rare He-3 gas	—	http://www.hep.shef.ac.uk/research/applied.php

*Described previously

(3) *What are the transport characteristics, fluxes and speciation of gases in environments with less than 1 km depth of relevance to geological repositories?* This question relates to the natural environment in and around geological repositories, but also the influence of perturbation during construction, operation and closure. In particular, the way the subsurface structural characteristics either facilitate or mitigate against the transport of gases within the repository is relevant.

(4) *Is the aim detection or quantification?* For example, in CCS, technologies that are sensitive to detecting the presence of CO₂ are not necessarily the best technologies for quantifying spatially variable saturation. In practice, early detection of unintended migration of CO₂ may enable mitigating activities to be undertaken, whereas quantification is important for calculating a mass balance and imposing financial penalties that are dependent upon the amount of CO₂ that escapes. While for RWD in almost any geology/geological environment, no leakage is achievable with appropriate, often costly, engineering.

Geophysics: technology transfer opportunities

A fundamental requirement for improving model capabilities, confidence in the results and in particular improving the modelling of gas flow through the subsurface is high-resolution data to categorize rock mass heterogeneities. Miniaturized, portable, low-power sensor technologies developed for space applications, which include X-ray diffraction (XRD), Raman spectroscopy and Fourier transform infrared spectroscopy (FT-IR) offer particular promise for on-site characterization of mineralogical heterogeneity of representative samples of the stratigraphy comprising and surrounding the repository, which might provide data and understanding to underpin models. Examples of possible technology transfer from space technology are given in Table 1.

Non-intrusive techniques can also be developed to allow characterization of the underlying geology. A promising technique belonging to the particle and nuclear physics sector (muon tomography), is based on the observation of cosmic-ray muons, sub-atomic particles produced in collisions of high-energy primary cosmic radiation with nuclei in the atmosphere, in the deep subsurface (Kudryavtsev *et al.*, 2012). This method allows for the mapping of geological structures. Muon detectors can be emplaced in the subsurface at different sites to monitor geological repositories. Although they may not be able to fully replace more conventional

techniques, they have a clear advantage of providing a continuous monitoring capability and possibly a significant saving on resources over a long time period.

Another non-intrusive technique used in the space exploration sector but with potential for use in geological repositories is Ground Penetrating Radar (GPR). Depth of penetration is strongly influenced by the subsurface substrate and presence of ice/water and salinity levels, but typically can be tens of metres. An example of a GPR system applied in space exploration is the WISDOM (Water Ice and Subsurface Deposit Observation On Mars) instrument on the planned ExoMars rover (ESA and Roscosmos) (Ciarletti *et al.*, 2011), which can penetrate up to 3 metres with cm-scale resolution. Such high-resolution subsurface analysis can be applied to monitoring the near-surface environment above a repository, particularly within terrains that would benefit from a miniaturized, low-power GPR. The MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) instrument on ESA's Mars Express orbiter (Mouginot *et al.*, 2012) (Table 1) also employs GPR technology and was originally designed to probe the ice-rich polar layered deposits up to four kilometres and up to several hundred metres in other lithic environments of Mars. Therefore this technology can also be applied in the identification of deep repositories.

Geochemistry

During the establishment of geological repositories, the local geochemical environment is perturbed. Some changes may be transient, but there may be long-term effects of the intervention of humans within the geological environment. For example, permanent changes to subsurface hydrology/groundwater flow regimes associated with repository construction (e.g. installation of low permeability walls) may lead to changes in redox states of subsurface fluids and minerals, most likely on a local scale. Questions related to geochemistry that may be particularly pertinent to geological repositories include:

(1) *How can we successfully obtain data that can be used to support the development of improved models such as the modelling of pore space chemical and physical processes and translate them to large-scale fate and transport models?* To understand the likely fate of radionuclides or supercritical CO₂ in the subsurface, we require simulation approaches supported by *in situ* geochemical monitoring and mapping.

(2) *What are the effects of impurities in the injected CO₂ streams (e.g. SO_x, NO_x, Hg in flue gas) on the nature and rates of chemical reactions during transport and injection, which would lead to mineralization and geologic sequestration of carbon?* We require better parameterization of interactions of impurities with other molecules, which is important to fully understand the groundwater chemistry and flow in deep systems (at repository depths).

(3) *In terms of storage security, what chemical reactions mobilize and immobilize CO₂ (including dissolution, residual saturation and mineralization as well as microbial effects)?* Once waste is contained it is necessary to monitor, long-term, the environment to determine whether waste is escaping and what geochemical reactions determine the rate of escape. This requires a more in depth investigation of geochemical reactions occurring in natural geological repository environments.

(4) *Can we identify potential geochemical signatures that could be used to indirectly indicate CO₂ leakage (i.e. other than measuring CO₂ itself) or the leakage of radionuclides into the environment?* During leakage of radioactive waste or CO₂, these substrates are likely to geochemically modify the surrounding environment. Both small-scale and large-scale monitoring methods can be used to detect potential geochemical alterations.

Geochemistry: technology transfer opportunities

Technology transfer areas include methods for detecting the migration of radionuclides, CO₂ and other gases that could be indicative of subsurface repository change or leakage, although time scale may be an issue. Of particular interest are spectroscopy techniques (e.g. infrared spectroscopy, gas chromatography coupled with mass spectrometry (GC-MS), X-ray diffraction (XRD)) developed for planetary exploration and astronomy. Both of these communities seek to develop small, low-energy, robust instruments with very high sensitivity, particularly when this instrumentation is being used to search for trace gases such as methane at the ppt/ppb/ppm level (e.g. Formisano *et al.*, 2004; Korabev *et al.*, 2013). An example of such technology is the Tunable Laser Spectrometer (TLS) of the Sample Analysis at Mars (SAM) suite of Curiosity rover used for the recent *in situ* methane detection on Mars (Webster *et al.*, 2015). Other examples include technologies to measure low concentrations of elements and impurities in the groundwater and in materials around a

geological repository during construction and potentially post-closure, such as X-ray fluorescence (XRF) (see Table 1 for examples of possible technology transfer).

Geobiology

Microorganisms are pervasive in the environment, including the deep subsurface (e.g. Wouters *et al.*, 2013). Near geological repositories, a variety of microbial metabolisms may be involved in changing the chemical speciation of elements and their mobility through the subsurface (Lloyd and Renshaw, 2005; Krawczyk-Barsch *et al.*, 2012), or in affecting the performance engineered barriers, or in enhancing canister corrosion, concrete deterioration and the structure and performance of bentonite buffer materials used in nuclear waste disposal scenarios (Masurat *et al.*, 2010; Pedersen, 2010), thereby affecting the performance of the engineered barriers and their functions (isolation and containment). Microorganisms and their activity can also change the transport properties of the host rocks of interest e.g. formation of biofilms can effect porosity (Coombs *et al.*, 2010). Despite the growing and impressive understanding of microbiology in the deep subsurface and microbial interactions with radionuclides, several key questions for biological science related to geological repositories can be identified:

(1) *What are the main processes by which the microbial communities associated with different lithologies can influence RWD and CCS?* We need to know more about subsurface microbial communities of geological materials at depth, and their dominant and potential metabolic pathways and how these respond to the changes imposed in and around a geological disposal facility. One way is to link the study of geological repository environments more directly with international continental and oceanic deep drilling programmes and especially permanent deep subsurface laboratories where long-term analysis of deep microbial communities can be accomplished.

(2) *How do activities during excavation, construction and operation inhibit or promote specific microbial processes?* During different phases of the development of a repository, new microbial inocula, interfaces and chemical species are likely to be introduced, which are expected to affect the resident microbial communities and their metabolic pathways. For instance, the introduction of oxygen during drilling or excavation is expected

to affect subsurface microbial consortia that were previously based on anaerobic metabolisms such as anaerobic respiration (iron and sulfate), fermentation or methanogenesis. There is a need to better understand the impact of the disturbance associated with reservoir or repository construction and active operation on the long term ecology of deep repository environments and associated implications for safe waste isolation.

Related to point (2) is a priority to better understand how communities change after the closure of the facility. Ideally one would monitor the evolving microbial community over time, linking back to changes in geochemical and geophysical properties. Although permanent deep subsurface laboratories make such monitoring possible, such laboratory facilities are limited to specific sites for logistics and cost reasons. Therefore, one obvious priority would be to advance our capacity to quantify and predict microbial dynamics across temporal and spatial scales, which is itself directly linked to improved capacities for geochemical modelling.

(3) *What are the effects of microbial presence and activity on local geochemistry, integrity of the repository and radionuclide transport? What are the exact roles of local microbial consortia in corrosion, as well as on microbial interactions with ground-water chemistry or radionuclides?* For example, there is knowledge on the capacity of deep microbial communities to produce or metabolize gases (including those that are relevant for RWD safety assessments e.g. methane and hydrogen), but not much is known on intermediate and final gas mass balances in a repository system and on the subsequent effects on the local chemical processes. Also the biodegradation of naturally occurring or introduced organic material and the organic matter derived from dead microorganisms (Bassil *et al.*, 2014) is expected to influence the local geochemistry.

(4) *What is the role of microbial biofilms in disposal systems?* In RWD, microbial biofilms on engineered interfaces such as concrete and metal can harbour strong chemical gradients which increase material deterioration rates, and can interact with radionuclides, changing geochemistry in a micro-environment. In CCS scenarios, extensive biofilms may interact with supercritical fluids. It is also not clear how microbial biofilm development is triggered and maintained in undisturbed and perturbed deep subsurface environments.

(5) *How can our current experiment-based understanding of microbial processes and their effects be abstracted and up-scaled, both in time*

and in space? Microbial influences can be studied in the laboratory or, in cases where the subsurface can be directly accessed, either by sample collection during initial drilling, in deep subsurface laboratories, or during the construction of the geological repository itself. However, a crucial objective must be to understand possible future interactions using improved modelling supported by empirical microbiological data. For example, there is a need to establish input values such as rates of metabolism for different redox couples for a given environment, and the rate of dispersal or transport of metabolic products and organic matter throughout the subsurface medium.

(6) *Can analogue environments be found that are representative of a geological repository environment?* The use of modelling, laboratory studies and *in situ* investigations will advance our understanding of microbial interactions in geological repositories. However, one means to achieve improved modelling and real-world data is to find easily accessible and representative analogue environments. One such environment is the Boulby International Subsurface Astrobiology Laboratory (BISAL) dedicated to astrobiology analogue research in the deep subsurface and for the testing of space technology and technology transfer into the mining environment at 1.1 km depth in the Boulby Mine (Yorkshire, UK) (Cockell *et al.*, 2013).

Geobiology: technology transfer opportunities

These identified challenges can be consolidated under technological innovation objectives that can be accomplished with technology transfer from a variety of areas, including molecular biology approaches, such as methodologies for the production of metagenomic libraries and their archiving and analysis. One promising area of research from the space sector that may find application to geological repositories is the ‘lab on a chip’ technology such as the Life Marker Chip (see Table 1), an instrument capable of recognizing small biomarker molecules by the use of an antibody-based detection system and developed for use on spacecraft (Sephton *et al.*, 2013). This approach is a good example of a portable/low-power microfluidics technology that is transferable to the deep subsurface. In general, this technology allows rapid identification of individual microbes and screening for specific metabolisms and metabolites that would allow for *in situ* analysis of microbial dynamics.

Other technologies, such as synchrotron spectroscopies offer the chance to better understand the

interactions of microorganisms with radionuclides and the secondary mineral products formed following these interactions. The possibility of examining these effects at small spatial scales, e.g. using new techniques such as STXM (scanning transmission X-ray microscope), allows for improved mechanistic understandings of these interactions that could be applied at the larger scale. Computational resources (possibly including all aspects of modelling and data analysis, processors, etc) from space physics and other areas could be mobilized to improve the ability to model microbial-groundwater interactions over time, and predict the effects of geological repository construction on geochemical and geobiological processes.

Concluding remarks

This paper concludes with the observation that there are strong synergies between high-technology areas such as space sciences and particle physics and the development of geological repositories. These synergies primarily arise because: (1) all these groups seek to build miniature, reliable, low energy, rugged instruments and (2) the scientific questions they address have similar technological solutions. Some concrete examples of these links are summarized in Table 1. We recommend that a stronger effort be made to link science and technology requirements in the development of geological repositories to these high-technology communities and ultimately to pool expertise and resources in the development of technology.

Acknowledgements

GeoRepNet is funded by the Science and Technology Facilities Council (STFC) as a Futures Programme Global Challenge Network (Grant No. ST/K001736/1). J. Wragg publishes with permission of the Executive Director of the British Geological Survey.

References

- Atreya, S.K. *et al.* (2013) Primordial argon isotope fractionation in the atmosphere of Mars measured by the SAM instrument on Curiosity and implications for atmospheric loss. *Geophysical Research Letters*, **40**, 5605–5609.
- Bassil, N.M., Bryan, N. and Lloyd, J.R. (2014) Microbial degradation of isosaccharinic acid at high pH. *ISME Journal*, **9**, 310–320.
- Benson, S.M. and Cook, P. (2005) Underground geological storage. Chapter 5 in: *Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change special report. IPCC, Interlachen, Switzerland.
- Birkholzer, J., Houseworth, J. and Tsang, C.-F. (2012) Geologic disposal of high-level radioactive waste: Status, key issues, and trends. *Annual Review of Environment and Resources*, **37**, 79–106.
- Blake, D. *et al.* (2012) Characterization and calibration of the CheMin mineralogical instrument on Mars Science Laboratory. *Space Science Reviews*, **170**, 341–399.
- Brinckerhoff, W.B. *et al.* (2013) Mars Organic Molecule Analyzer (MOMA) mass spectrometer for ExoMars 2018 and beyond. *Aerospace Conference, 2013 IEEE*, DOI: 10.1109/AERO.2013.6496942
- Ciarletti, V., Corbel, C., Plettemeier, D., Cais, P., Clifford, S.M. and Hamran, S.E. (2011) WISDOM GPR designed for shallow and high-resolution sounding of the Martian subsurface. *Proceedings of the IEEE*, **99**, 824–836.
- Coates, A.J. *et al.* (2012) Lunar PanCam: Adapting ExoMars PanCam for the ESA Lunar Lander. *Planetary and Space Science*, **74**, 247–253.
- Cockell, C.S., Payler, S., Paling, S., and McLuckie, D. (2013) The Boulby International Subsurface Astrobiology Laboratory. *Astronomy & Geophysics*, **54**, 2.25–2.27.
- Coombs, P., Wagner, D., Bateman, K., Harrison, H., Milodowski, A.E., Noy, D. and West, J.M. (2010) The role of biofilms in subsurface transport processes. *Quarterly Journal of Engineering Geology and Hydrogeology*, **43**, 131–139.
- Cousins, C.R., Gunn, M., Prosser, B.J., Barnes, D.P., Crawford, I.A., Griffiths, A.D., Davis, L.E. and Coates, A.J. (2012) Selecting the geology filter wavelengths for the ExoMars Panoramic Camera instrument. *Planetary and Space Science*, **71**, 80–100.
- Dave, A. *et al.* (2013) The sample handling system for the Mars Icebreaker Life Mission: From dirt to data. *Astrobiology*, **13**, 354–369.
- Davies, P. *et al.* (2007) UK lunar science missions: Moonlite & Moonraker. 3rd International Conference on Recent Advances in Space Technologies, Vols. 1 and 2, 774–779.
- de Vera, J.P., Dulai, S., Kereszturi, A., Koncz, L., Lorek, A., Mohlmann, D., Marschall, M. and Pocs, T. (2014) Results on the survival of cryptobiotic cyanobacteria samples after exposure to Mars-like environmental conditions. *International Journal of Astrobiology*, **13**, 35–44.
- Edwards, H.M., Hutchinson, I. and Ingley, R. (2012) The ExoMars Raman spectrometer and the identification of biogeological spectroscopic signatures using a flight-like prototype. *Analytical and Bioanalytical Chemistry*, **404**, 1723–1731.
- Ehresmann, B. *et al.* (2014) Charged particle spectra obtained with the Mars Science Laboratory Radiation Assessment Detector (MSL/RAD) on the surface of

- Mars. *Journal of Geophysical Research-Planets*, **119**, 468–479.
- Evans-Nguyen, T., Becker, L., Doroshenko, V. and Cotter, R.J. (2008) Development of a low power, high mass range mass spectrometer for Mars surface analysis. *International Journal of Mass Spectrometry*, **278**, 170–177.
- Fairen, A.G. *et al.* (2010) Astrobiology through the ages of Mars: The study of terrestrial analogues to understand the habitability of Mars. *Astrobiology*, **10**, 821–843.
- Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N. and Giuranna, M. (2004) Detection of methane in the atmosphere of Mars. *Science*, **306**, 1758–1761.
- Gao, Y. *et al.* (2008) Lunar science with affordable small spacecraft technologies: MoonLITE and Moonraker. *Planetary and Space Science*, **56**, 368–377.
- Glass, B.J., Dave, A., McKay, C.P. and Paulsen, G. (2014) Robotics and automation for "Icebreaker". *Journal of Field Robotics*, **31**, 192–205.
- International Atomic Energy Agency [IAEA] (2007) *Estimation of global inventories of radioactive waste and other radioactive materials*. IAEA-TECDOC-1591. IAEA, Vienna [http://www-pub.iaea.org/MTCD/publications/PDF/te_1591_web.pdf].
- Jenkins, C.R. *et al.* (2012) Safe storage and effective monitoring of CO₂ in depleted gas fields. *Proceedings of the National Academy of Sciences*, **109**, E35–E41.
- Josset, J.-L. *et al.* (2018) CLUPI, a high-performance imaging system on the ESA-NASA rover of the 2018 ExoMars mission to discover biofabrics on Mars. *Proceedings of the European Geoscience Union General Assembly 2012*, Vienna, p. 13616.
- Korablev, O., Grigoriev, A.V., Trokhimovsky, A., Ivanov, Y.S., Moshkin, B., Shakun, A., Dziuban, I., Kalinnikov, Y.K. and Montmessin, F. (2013) Atmospheric Chemistry Suite (ACS): a set of infrared spectrometers for atmospheric measurements on board ExoMars Trace Gas Orbiter. *Proceedings of SPIE, Infrared Remote Sensing and Instrumentation XXI*, Vol. **8867**, DOI: 10.1117/12.2026900
- Krawczyk-Barsch, E., Lunsdorf, H., Pedersen, K., Arnold, T., Bok, F., Steudtner, R., Lehtinen, A. and Brendler, V. (2012) Immobilization of uranium in biofilm microorganisms exposed to groundwater seeps over granitic rock tunnel walls in Olkiluoto, Finland. *Geochimica et Cosmochimica Acta*, **96**, 94–104.
- Kudryavtsev, V.A., Spooner, N.J.C., Gluyas, J., Fung, C. and Coleman, M. (2012) Monitoring subsurface CO₂ emplacement and security of storage using muon tomography. *International Journal of Greenhouse Gas Control*, **11**, 21–24.
- Lakdawalla, E. (2013) To the Moon with LADEE. *Nature Geoscience*, **6**, 988–988.
- Leshin, L.A. *et al.* (2013) Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity Rover. *Science*, **341**, DOI: 10.1126/science.1238937
- Lloyd, J.R. and Renshaw, J.C. (2005) Bioremediation of radioactive waste: radionuclide-microbe interactions in laboratory and field-scale studies. *Current Opinion in Biotechnology*, **16**, 254–260.
- Long, J.C.S. and Ewing, R.C. (2004) Yucca Mountain: Earth-science issues at a geologic repository for high-level nuclear waste. *Annual Review of Earth and Planetary Sciences*, **32**, 363–401.
- Lopez-Reyes, G. *et al.* (2013) Analysis of the scientific capabilities of the ExoMars Raman Laser Spectrometer instrument. *European Journal of Mineralogy*, **25**, 721–733.
- Masurat, P., Eriksson, S. and Pedersen, K. (2010) Microbial sulphide production in compacted Wyoming bentonite MX-80 under in situ conditions relevant to a repository for high-level radioactive waste. *Applied Clay Science*, **47**, 58–64.
- McKay, C.P. *et al.* (2013) The Icebreaker Life Mission to Mars: A search for biomolecular evidence for life. *Astrobiology*, **13**, 334–353.
- Ming, D.W. *et al.* (2014) Volatile and organic compositions of sedimentary rocks in Yellowknife Bay, Gale Crater, Mars. *Science*, **343**, DOI: 10.1126/science.1245267
- Mouginot, J., Pommerol, A., Beck, P., Kofman, W. and Clifford, S.M. (2012) Dielectric map of the Martian northern hemisphere and the nature of plain filling materials. *Geophysical Research Letters*, **39**, L02202.
- NUREG-1350 (2013) *2013–2014 Information Digest*. vol. **25**. U.S. Nuclear Regulatory Commission (NRC), Office of Public Affairs Washington, DC.
- Parro, V. *et al.* (2011) SOLID3: a multiplex antibody microarray-based optical sensor instrument for in situ life detection in planetary exploration. *Astrobiology*, **11**, 15–28.
- Parro, V. *et al.* (2005) Instrument development to search for biomarkers on Mars: Terrestrial acidophile, iron-powered chemolithoautotrophic communities as model systems. *Planetary and Space Science*, **53**, 729–737.
- Pedersen, K. (2010) Analysis of copper corrosion in compacted bentonite clay as a function of clay density and growth conditions for sulfate-reducing bacteria. *Journal of Applied Microbiology*, **108**, 1094–1104.
- Preston, L.J. and Dartnell, L.R. (2014) Planetary habitability: lessons learned from terrestrial analogues. *International Journal of Astrobiology*, **13**, 81–98.
- Rütters, H. and the CGS Europe partners (2013) State of play on CO₂ geological storage in 28 European countries. *CGS Europe report No. D2.10*, June 2013, 89 pp.
- Sarantos, M., Killen, R.M., Glenar, D.A., Benna, M. and Stubbs, T.J. (2012) Metallic species, oxygen and silicon in the lunar exosphere: Upper limits and

- prospects for LADEE measurements. *Journal of Geophysical Research: Space Physics*, **117**, 1–16.
- Scott, V., Gilfillan, S., Markusson, N., Chalmers, H. and Haszeldine, R.S. (2013) Last chance for carbon capture and storage. *Nature Climate Change*, **3**, 105–111.
- Sephton, M.A., Sims, M.R., Court, R.W., Luong, D. and Cullen, D.C. (2013) Searching for biomolecules on Mars: Considerations for operation of a life marker chip instrument. *Planetary and Space Science*, **86**, 66–74.
- Sims, M.R. *et al.* (2012) Development status of the life marker chip instrument for ExoMars. *Planetary and Space Science*, **72**, 129–137.
- Sobrado, J.M., Martin-Soler, J. and Martin-Gago, J.A. (2014) Mimicking Mars: A vacuum simulation chamber for testing environmental instrumentation for Mars exploration. *Review of Scientific Instruments*, **85**, 35111–35111.
- Solente, N., Bergmans, A., Garcia-Sineriz, J.-L., Clark, A., Breen, B. and Jobmann, M. (2013) Overview of the MoDeRn project: A reference framework for developing a monitoring programme. Monitoring in Geological Disposal of Radioactive Waste (MoDeRn) Conference, Luxembourg. Abstract at http://www.modern-fp7.eu/fileadmin/modernconference/Presentations/S1/S102A_Overview_of_the_MoDeRn_project_Solente.pdf
- Stoker, C.R. *et al.* (2008) The 2005 MARTE Robotic Drilling Experiment in Rio Tinto, Spain: objectives, approach, and results of a simulated mission to search for life in the Martian subsurface. *Astrobiology*, **8**, 921–945.
- Stubbs, T.J., Glenar, D.A., Colaprete, A. and Richard, D.T. (2010) Optical scattering processes observed at the Moon: Predictions for the LADEE Ultraviolet Spectrometer. *Planetary and Space Science*, **58**, 830–837.
- Todd, J.F.J. *et al.* (2007) Ion trap mass spectrometry on a comet nucleus: the Ptolemy instrument and the Rosetta space mission. *Journal of Mass Spectrometry*, **42**, 1–10.
- Toth, F.L. (2011) Geological disposal of carbon dioxide and radioactive waste: A comparative assessment. Pp. 24–27 in: *Advances in Global Change Research*, vol. **44**, Springer.
- Trebi-Ollennu, A., Rankin, A.L., Cheng, Y., Tso, K.S., Deen, R.G., Aghazarian, H., Kulczycki, E.A., Bonitz, R.G., Alkalai, L. and IEEE. Instrument deployment testbed: For planetary surface geophysical exploration. *Aerospace Conference, 2013, IEEE*, DOI:10.1109/AERO.2013.6497157
- Vines, S. and Beard, R. (2012) An overview of radionuclide behaviour research for the UK geological disposal programme. *Mineralogical Magazine*, **76**, 3373–3380.
- Webster, C.R. *et al.* (2015) Mars methane detection and variability at Gale crater. *Science*, **23**, 415–417.
- Wilkinson, M., Haszeldine, R.S., Mackay, E., Smith, K. and Sargeant, S. (2013) A new stratigraphic trap for CO₂ in the UK North Sea: Appraisal using legacy information. *International Journal of Greenhouse Gas Control*, **12**, 310–322.
- Wong, M.H. *et al.* (2013) Isotopes of nitrogen on Mars: Atmospheric measurements by Curiosity's mass spectrometer. *Geophysical Research Letters*, **40**, 6033–6037.
- Wouters, K., Moors, H., Boven, P. and Leys, N. (2013) Evidence and characteristics of a diverse and metabolically active microbial community in deep subsurface clay borehole water. *FEMS Microbiology Ecology*, **86**, 458–473.
- Yuen, P., Gao, Y., Griffiths, A., Coates, A., Muller, J.P., Smith, A., Walton, D., Leff, C., Hancock, B. and Shin, D. (2013) ExoMars rover PanCam: Autonomy and computational intelligence. *IEEE Computational Intelligence Magazine*, **8**, 52–61.
- Zacny, K. *et al.* (2013) Reaching 1m deep on Mars: The Icebreaker drill. *Astrobiology*, **13**, 1166–1198.
- Zimmerman, W., Blake, D., Harris, W., Morookian, J.M., Randall, D., Reder, L.J., Sarrazin, P. and IEEE (2013) MSL Chemistry and Mineralogy X-ray Diffraction X-ray Fluorescence (CheMin) Instrument. *Aerospace Conference, 2013 IEEE*, DOI: 10.1109/AERO.2013.6496835