Proceedings of the NAWG-15 Workshop, 23-26th May, 2017, Rez, Czech Republic.

Bedrock Geosciences Technical Report 2023-01

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1. Introduction

1.1 Overview of the workshop

The 15th Workshop of the Natural Analogue Working group (NAWG) was held in the meeting rooms of the UJV laboratory in Rez, near Prague, Czech Republic (see Figure 1-1). The workshop ran from Tuesday, 23rd through to Friday, 26th May, 2017 and consisted of 3 days of presentations and discussion followed by a full-day field trip (see Table 1-1).

Figure 1-1: View of the UJV laboratory, Rez, Czech Republic (image courtesy UJV)

Table 1-1: NAWG-15 - final workshop agenda

Tuesday 23rd May		
	Introduction and registration	
08:45 – 09:00	Opening of the course and organisational aspects	Venda Havlova & Russell Alexander
Session I	**To explore the current use of natural analogues in developing and supporting the safety case - presentations**	**Chair: Russell**
09:00 – 10:00	Use of natural analogues in the UK safety case	Simon Norris RWM Ltd, UK
10:00 – 10:30	*Coffee/tea*	
10:30 – 11:00	Safety case communication - interim report of the NEA *Integrated Group for the Safety Case*	Ulrich Noseck GRS, Germany
11:00– 11:30	Use of natural analogues in the Finnish safety case – status update on the Complementary Considerations approach	Heini Reijonen GTK, Finland

11:30 – 12:30	Spent Nuclear Fuel Management in the Czech Republic: Progress Concerning Deep Geological Repository Development	Jiří Slovák, SURAO, Czech Republic
12 :30 – 13:45	*Lunch*	
Session I (cont.)	**To explore the current use of natural analogues in developing and supporting the safety case - discussions in small groups**	**Chair: Russell**
13:45	Points to be considered include: • relative weighting of laboratory, URL, modelling results and NA • 'ground truthing' of modelling results via NA input – is that the limit? • Why so little NA in SC, does it have an image problem?	
15:30-16:00	*Coffee/tea*	
16:00	Presentation of main points from the discussion	
ca. 17:00	Session I wrap-up	
Session II	**Posters: posters will be on show throughout the workshop**	
NAWG-15 Workshop Dinner 19:00		
Wednesday 24th May		
Session III	**To explore the current use of NA in communicating both the results of the SC and also the wider aspects of radwaste disposal**	**Chair: Venda**
09:00 – 10:00	The use of natural analogues in building links with municipal and First Nation stakeholders in the NWMO site selection process	Alec Blyth NWMO, Canada
10:00 – 10:30	*Coffee/tea*	
10:30 – 11:30	Communicating the results of the EU-research project Carbon-14 Source Term	Erika Neeft Covra, The Netherlands
11:30 – 12:15	Discussion	
12:15 – 13:30	*Lunch*	
Session IV	**NA studies of repository processes**	**Chair: Radek**
13:30-14:00	Investigation of postglacial faults in Finland - an update	Timo Ruskeeniemi GTK, Finland
14:00-14:30	Using natural analogue observations for testing large scale numerical models of oxygen intrusion in fractured rocks	Jorge Molinero Amphos21, Spain

14:30-15:00	Palaeohydrology of the Sellafield region	Tony Milodowski BGS, UK
15:00-15:30	*Coffee/tea*	
15:30-16:00	Natural U distribution at the KURT site	Jang-Soon Kwon KAERI, RoK
16:00-16:30	Potential for fractured higher strength rocks to uptake radionuclides from groundwater – a natural analogue study	Simon Norris RWM Ltd, UK
16:30–17:00	The Greenland Analogue Project (GAP) overview	Jon Engström, GTK, Finland
17:00-close		
Thursday 25th May		
Session V	**NA of repository materials**	
Session Va	**Waste forms and waste containers**	**Chair: Simon**
09:00-09:30	Archaeology analogues for geological disposal of spent nuclear fuels (SNFs) – current status and future outlook in Taiwan	Polly Tsai INER, RoC
09:30-10:00	Natural glasses as NA for vitrified HLW	Venda Havlova UJV, Czech Republic
10:00-10:30	*Coffee/tea*	
10:30-11:00	NA studies of cementitious systems	Russell Alexander Bedrock Geosciences, Switzerland
1100 – 1200	Copper canister natural analogues	Heini Reijonen GTK, Finland
12:00-12:30	The oldest steel in the world?	Russell Alexander Bedrock Geosciences, Switzerland
12:30-13:30	*Lunch*	
Session Vb	**NA studies of the long-term behaviour of the bentonite buffer**	**Chair: Walter**

13:30-14:00	Stability of smectite under hyperalkaline fluids which include high levels of Fe, Mg and Al ions	Naoki Fujii RWMC, Japan
14:00-14:30	International Bentonite Longevity (IBL) project: an introduction	Heini Reijonen GTK, Finland
14:30-15:00	Natural analogue study on the effect of loading on bentonite deformation	Tatsuya Kijima, NRA, Japan
15:00-15:30	*Coffee/tea*	
15:30-16:00	Longevity of borehole seals: NA input and open questions	Russell Alexander Bedrock Geosciences, Switzerland
16:00	Workshop wrap-up	Venda Havlova, Radek Cervinka & Russell Alexander
Friday 26th May		
Session IV	**Field excursion: Visit SURAO's new Bukov URL in the former Rozna uranium mine**	**07:00 – 18:00**

As can be seen from Table 1-1, the workshop agenda consisted of several sessions with a mix of natural analogue (NA) topics of relevance to radioactive waste disposal:

- Near-field studies, including:
    - Analogues of various waste forms
    - Canister studies
    - Buffer and backfill/plug and seal analogues
- Far-field studies, including:
    - Radionuclide retardation in the geosphere
- Recent examples of NA support of the safety case (SC)
- Stakeholder communication with NAs

The full-day field trip was to SURAO's new Bukov URL in the former Rozna uranium mine (see https://www.pvpbukov.cz/en/home-page/ for details).

The participants (Table 1-2) came from a range of organisations from some ten countries worldwide.

Table 1-2: List of NAWG-15 workshop participants

Name	Organisation
Russell Alexander	Bedrock Geosciences, CH
Alec Blyth	NWMO, C

Zita Bukovská	Czech Geological Survey, CZ
Radek Cervinka	UJV, CZ
Ian Crossland	Crossland Consulting, UK
Jon Engström	GTK, FI
Naoki Fujii	RWMC, J
Venda Havlova	UJV, CZ
Milan Hokr	Technical University of Liberec, CZ
Iveta Holánová	SURAO, CZ
Šimon Hradní	SÚRAO, CZ
Masakazu Ito	Kunimine Industries Company, J
Tatsuya Kijima	NRA, J
Miloš Kováčik	SURAO, CZ
Jang-Soon Kwon	KAERI, RoK
Fiona McEvoy	BGS, UK
Richard Metcalfe	Quintessa UK
Tony Milodowski	BGS (retired), UK
Georgio Mingrone	Sogin S.p.A., I
Jorge Molinero	Amphos, E
Erika Neeft	COVRA, NL
Masanobu Nishimura	Obayashi, J
Simon Norris	RWM Ltd, UK
Ulrich Noseck	GRS, D
Nikol Novotná	SÚRAO, CZ
Heini Reijonen	GTK, FI
Timo Ruskeeniemi	GTK, FI
Jiří Slovák	SÚRAO, CZ
Lucie Steinerová	SÚRAO, CZ
Jan Stoulil	University of Chemistry and Technology, Prague, CZ
Shih-Chin Tsai	National Tsing Hua University, RoC
Tsuey-Lin (Polly) Tsai	INER, RoC
Stefania Uras	Sogin S.p.A., I
Antonín Vokál	SÚRAO, CZ

1.2 Why natural analogues - assessing repository performance at long times?

A major challenge in the development of a SC for a deep geological repository is dealing with the long period of time over which the wastes remain hazardous. Over such a period, a wide range of events and processes acts on a repository and it's geological and surface environment. These events and processes, taking place over different time windows and at local to regional scales, result in increasing uncertainty in the future evolution of the repository and its environment. This means that arguments must be developed to show that this uncertainty can be addressed in a manner that is not only acceptable to regulators, who may in any case set out the types of arguments they want to see, but also convincing to less technical audiences who need to trust in the safety of the repository. Thus, complementary lines of argument are required to compensate for increasing uncertainties affecting calculated releases at distant times.

However, complementary arguments[1] can also be made to address other aspects of safety, especially continuing isolation of the wastes, even at times beyond when quantitative safety assessments (SA) can be supported. NEA (2009) suggests that "complementary arguments might be based, for example, on the absence of resources that could attract inadvertent human intrusion and on the geological stability of the site, with low rates of uplift and erosion". Another challenge with the long period addressed by the SC is that, although some experiments can be carried out in the laboratory, in underground research facilities (thus in the actual or similar host rock and geological environment) or in the field, these cover short timescales compared with long-term repository evolution. To try and address this specific problem, complementary arguments are made using analogous geological and/or anthropogenic examples of the materials and processes of interest (see the discussion on NA, below) to show that understanding is good enough to extrapolate short-term experimental results to long-term performance.

A further challenge arising from the long time periods of interest in the SC relates to how safety is quantified over these very long times. The most common indicators of safety are individual dose and risk (NEA 2002) and, of these, dose is much easier to communicate to a wider audience as it can be compared, for example, with the natural background radiation or medical radiation exposure (comparisons which are themselves complementary arguments).

Within the SC, quantitative SA using models and data tends to focus on potential radionuclide releases from a repository to the biosphere or surface environment. The uncertainties affecting the models can generally be quantified or bounded and dealt with in the SA by using cautiously chosen parameter values, conservative model assumptions or evaluating multiple cases covering the ranges of uncertainty. However, where the consequences of calculated releases are to be expressed in terms of dose, the biosphere must also be modelled. The models of the way in which humans are exposed (e.g. ingestion via consumption of food or drinking of water) are closely related to human habits that can be predicted with confidence only in the very short term, basically in the order of decades.

To complement the quantitative estimates of doses, especially in the period beyond a few tens of thousands of years, additional complementary safety indicators have been proposed (e.g. IAEA 2003) using fluxes and concentrations of naturally-occurring radionuclides in the undisturbed biosphere or geosphere for comparison with the calculated radionuclide releases from the repository. IAEA (2003) also found that alternative indicators such as "crossover times" could be useful in illustrating safety. A crossover time is the point in time in the future at which either the activity or radiotoxicity of the radionuclides remaining in the engineered barriers or released to the geosphere decrease due to radioactive decay below the corresponding values for relevant natural materials such as the original uranium ore or the excavated host rock. Both these areas were explored in Alexander et al (2015a).

1.3 Introduction to natural analogues – what are they and how do they help us assess safety?

The main arguments employed here relate to NAs of the repository systems or processes. As noted in Miller et al. (1994, 2000), argumentation by use of analogy is well established in many fields including philosophy, biology, linguistics and law (Petit, 1992), and most scientists are familiar with this approach and will have used it at some point in their career. For example, in the oil industry, accessible (surface) analogues of the geological conditions expected in physically inaccessible deep oil and gas reservoirs are often studied.

[1] Also termed 'complementary considerations', see Posiva (2013a, 2022)

For the specific case of radioactive waste disposal, the main inaccessible features are:

- the very long time it will take for long lived waste to decay to safe levels – how can anyone know how the materials which are used to contain the wastes will behave over thousands to millions of years?
- the large spatial scales which cannot be directly addressed in a laboratory – how can the migration of radionuclides through several hundred metres of host rock from the repository to the earth's surface be studied and modelled?
- the heterogeneity and structural complexity of the geological environment which will host the repository – how can this ever be approached in a laboratory or modelled on a computer?

Hence the study of natural (predominantly geological) systems has been termed natural analogue research within the radioactive waste disposal community and the term "NA" has developed a particular meaning associated with providing supporting arguments for a repository SC (see, for example, Chapman et al. 1984; Côme & Chapman 1986; Miller et al. 1994, 2000; Posiva 2013a, 2023; Reijonen & Alexander, 2024, for discussion). As noted above, the key factors here are the heterogeneity and complexity of natural systems and, in particular, the very large dimensions and long timescales over which safety must be assured.

Due to the long timescales of concern, the basis of most SCs is a quantitative evaluation that is based on complex mathematical models and their general lack of transparency only adds to the mistrust of many stakeholders. How then can people be convinced that it is possible to assess the performance (and thus ensure the safety) of a repository over the long timescales of interest? One way is to address the robustness of the SA models, by clearly indicating the form and extent of model testing carried out within the repository SA. Not only can this show that the individual component parts of the complex structure which constitutes most SA models have been checked, but also that the 'mathematical black boxes' (cf. Alexander et al. 2003) constitute an acceptable representation of the repository system.

As noted by Alexander et al. (1998), part of the problem undoubtedly lies in the unusual nature of radioactive waste disposal: in most major engineering projects, such as bridge construction or aerospace engineering, the designs are tested against a range of laboratory experiments backed up by expert judgement based on experience with the same or similar systems. Here repository design deviates from standard engineering practice in that only a few repositories currently exist and testing their compliance to design limits will be impossible due to the timescales involved. In addition, peoples' anxiety about most things radioactive means that they require some greater form of 'proof' that a repository is safe than they are willing to accept for other engineered systems (see discussion in West et al., 2002). This being the case, significant additional effort has been expended within the radioactive waste disposal community to make it clear that the SA models can adequately predict the long-term behaviour of a repository.

1.4 What is a natural analogue?

Traditionally, SA modellers have placed much weight on laboratory data for the construction and testing of their SA models and, with only a few exceptions (e.g. Posiva, 2013b, 2023), have not integrated in their SA reports data from either NAs or in situ experiments in URLs (see discussion in Alexander et al., 1998; Reijonen & Alexander, 2024). The over-dependence on laboratory data is understandable in that the information is produced under well understood, fully controlled conditions and thus the modellers feel they can place a high degree of confidence in the results obtained. Unfortunately, the full complexity of a repository cannot be re-created in a laboratory and it is necessary to address processes which are influenced by natural heterogeneities, which include large degrees of uncertainty and which operate over very long timescales. In this case, it is necessary to supplement laboratory data with information from in situ URL experiments and NAs. The potential evolution of geological repositories can be simulated by the use of mathematical models, but the extent to which such models can be validated by conventional approaches is inherently limited. Here NAs have an unique role to play.

In its basic form, a NA study can be any form of investigation of any relevant natural system, as long as it provides quantitative (or even qualitative) information which can be used to support (and build confidence in) geological disposal. This may mean that a study provides data which are directly applicable to the SC or, alternatively, it may provide illustrations of concepts or processes which can demonstrate safety (see, for example, Reijonen et al., 2015, Posiva, 2023, Alexander & Reijonen, 2924 for discussion). Each repository design will require unique information to assist in building and presenting the SC but, historically, NA studies have tended to focus on only a narrow range of natural systems. They can thus be categorised into a few broad groups which are representative of some major components of a repository system or feature of its evolution, namely:

- natural geological and geochemical systems
- archaeological systems
- sites of anthropogenic contamination

It should be noted, however, that this focus is currently changing: Reijonen et al. (2015), for example, present an example of a more broad-based approach to the use of NA in supporting the SC whereas Baik et al. (2015) and Wolf & Noseck (2015) look to define specific forms of NA support for repositories in crystalline and evaporite host rocks, respectively.

It is beyond the scope of this report to provide an overview of the vast range of NAs that have been studied; for this the reader is invited to examine publications focussed on just that, such as Miller et al. (2000, 2006), Degnan et al. (2005), Brasser et al. (2008) and Alexander & Reijonen (2024).

1.5 NAWG – the Natural Analogue Working Group

In an attempt to define NA studies more clearly, and to orient them towards individual processes for which good analogues can be found, Chapman et al. (1984) listed a set of guidelines for selecting NAs for investigation. The need for well-characterised, process-oriented NA studies is reaffirmed in this report and thus these guidelines are repeated here:

1) The process involved should be clear-cut. Other processes which may have been involved in the geochemical system should be identifiable and amenable to quantitative assessment as well, so that their effects can be subtracted.
2) The chemical analogy should be good. It is not always possible to study the behaviour of a mineral system, chemical element or isotope identical to that whose behaviour requires assessing. The limitations of this should be fully understood.
3) The magnitude of the various physico-chemical parameters involved (pressure, temperature, pH, Eh, concentration etc.) should be determinable, preferably by independent means and should not differ greatly from those envisaged in a repository.
4) The boundaries of the system should be identifiable (whether it is open or closed, and consequently how much material has been involved in the process being studied).
5) The timescale of the process must be measurable, since this factor is of the greatest significance for a natural analogue.

The quantitative philosophy outlined by Chapman et al. (1984) proved to be the impetus for a greater interest in natural analogues which resulted in an international symposium (Smellie, 1984) and the formation of the Natural Analogue Working Group (NAWG) which was originally sponsored by the Commission of the European Communities (CEC, now EC). Since its inception, these themes have been addressed at 16 international NAWG workshops (including NAWG-16, the focus of this report):

- 14th Workshop took place on 9-11th June, 2015 in Rauma, Finland. Here, the application of NAs to repository SA was discussed (see Alexander et al, 2015a for details)
- 13th Workshop took place on 13-16th May, 2013 in Nagoya, Japan. A wide area of NA study was covered and some 9 of the presentations were published in the Swiss Journal of Geosciences (volume 108, 2015)
- 12th Workshop took place on 11-13th May, 2011 in Larnaca, Cyprus where predominantly NAs of engineered barriers were discussed. The main presentations at NAWG 12 are available at https://www.natural-analogues.com/nawg-workshops/nawg-12-2011-cyprus
- 11th Workshop: Liverpool, UK, 2009 where a short meeting was held at the 12th ICEM (International Conference on Environmental Remediation). No proceedings were produced
- 10th Workshop: Munich, Germany, 2007 where the workshop examined how current and future studies could be better focussed on providing appropriate data for the various end-users of natural analogue data. The main presentations at NAWG 10 are available at https://www.natural-analogues.com/nawg-workshops/nawg-10-2007-germany
- 9th Workshop: Aarau, Switzerland, 2002, where a short meeting was held with the theme being the current international status of natural analogues. No proceedings were produced
- 8th Workshop: Strasbourg, France, 1999, was devoted to a presentation of three, major international natural analogue projects, Oklo (II), Palmottu and Pena Blanca. See https://www.natural-analogues.com/nawg-workshops/other-nawg-workshops for a link to the proceedings
- 7th Workshop: Stein am Rhein, Switzerland, 1996, where one of the main themes of the workshop was the application of natural analogues to toxic wastes (EUR 17851 EN)
- 6th Workshop: Santa Fe, USA, 1994, where the intention was to review the "state-of-the-art" of several key issues in near-field and far-field processes and their importance to PA with the intention to provide a consensus view of the remaining areas requiring further research in natural analogues. See https://www.natural-analogues.com/nawg-workshops/other-nawg-workshops for a link to the proceedings (von Maravic & Smellie, 1995)
- 5th Workshop: Toledo, Spain, 1992, was held in association with the final workshop of the Alligator Rivers Analogues Project. See https://www.natural-analogues.com/nawg-workshops/other-nawg-workshops for a link to the proceedings
- 4th Workshop: Pitlochry, Scotland, 1990, was devoted to review 5 years of NA studies and the final conclusions drawn from the Poços de Caldas study. See https://www.natural-analogues.com/nawg-workshops/other-nawg-workshops for a link to the proceedings
- 3rd Workshop: Snowbird, USA, 1988, where the application of natural analogues to repository performance assessment was discussed (Come & Chapman, 1988)
- 2nd workshop: Interlaken, Switzerland, 1986, where anthropogenic analogues and the role of colloids, complexes and microbes have been reviewed (Come & Chapman, 1986)
- 1st Workshop: Brussels, Belgium, 1985, where the theme was the interaction between the modellers and experimenters. See https://www.natural-analogues.com/nawg-workshops/other-nawg-workshops for a link to the proceedings

NAWG reports are a particularly valuable record of the evolution and application of NA studies. Most of the large and significant analogues have been represented at NAWG meetings. Furthermore, the

NAWG reports attempt to develop the perception of NAs by giving agreed introductory statements on their development.

Advances made since the formation of NAWG include:

- Studying NAs has greatly increased the understanding of repository-relevant processes and improved the capability to describe and effectively model them
- The larger, multi-objective NA studies can be a very cost-effective way of training site characterisation and SA groups on real, complex systems (if properly integrated)
- The application of NAs in broadening public perception of the natural context of waste disposal has become increasingly important
- An increased awareness of the potential for studying NAs of chemo-toxic waste (e.g. Alexander & McKinley, 1999; Wilson et al., 2009) and understanding the long-term impacts of CO_2 sequestration (see, for example, Benson et al., 2005 and https://www.natural-analogues.com/nawg-library/ccs)

NAWG continues to grow (please see https://www.natural-analogues.com/background/nawg-members for details) and NAWG workshops will continue to be held biennially for the foreseeable future.

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2. Extended abstracts (alphabetical order)

Copper analogues – status and future outlook

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I. INTRODUCTION

Copper is used in several high-level radioactive waste disposal package designs. These include repository concepts KBS-3 [1] and Mark-II [2] (Swedish and Canadian concepts, respectively). In the KBS-3 concept, waste package consists the iron insert surrounded by copper overpack about 5cm thick, while Mark-II concept, there is a thin outer coating of copper of around 3-10 mm (aa cold copper spray) [3].

Long-term durability of the copper components need to be evaluated for the safety cases. There are some copper analogues, both archaeological and natural native copper, that have been used to evaluate safety , but the available data is insufficient to provide much quantitative information and this is especially true in regards to durability of natural metallic copper in geological environments. Here, we present the potential for future studies of copper corrosion to support safety cases by producing more quantitative data that can be used in the safety case, allowing optimisation of design as well as building confidence for the results of corrosion modeling.

II. COPPER ANALOGUES IN SAFETY CASES

In recently published safety cases by Posiva and SKB, copper analogues are used mainly to provide qualitative support for the modeling of corrosion [1,4]. Some quantitative analyses are available for archaeological copper analogues, but quantitative studies of natural native copper are currently lacking.

III. POTENTIAL FOR NEW STUDIES

A reconnaissance trip was organised by GTK to visit Keweenaw Peninsula, Michigan USA a place well known of its native copper occurrences (Fig.1). The Keweenaw Peninsula native copper mining district yielded 5 billion kg of refined copper from natural native copper from 1845 to 1968; the world's largest mineable accumulation of native copper. The widespread occurrence of native copper in this area results in its being subjected to a wide range of geochemical conditions in the natural environment over various lengths of time. The major settings are described below.

In situ native copper (relevant for ~1000 Ma to present time frames) from underground mine sites and outcrops is found in different occurs as microscopic to multiple ton masses of native copper as well as well developed crystals of native copper. In the variety of natural setting, the native copper has been exposed to anoxic to oxic conditions and near surface fresh groundwaters to saline brines.

Transported native copper (relevant for 10 000 years to present timeframes) was plucked from the bedrock by Quaternary glaciers and larger cleaned by abrasion by rocks carried in the ice. These small to multiple ton sized sculpted masses of native copper ("float copper") are found in Quaternary deposits where they have been exposed to both unsaturated/saturated and oxic/anoxic conditions (Fig. 2).

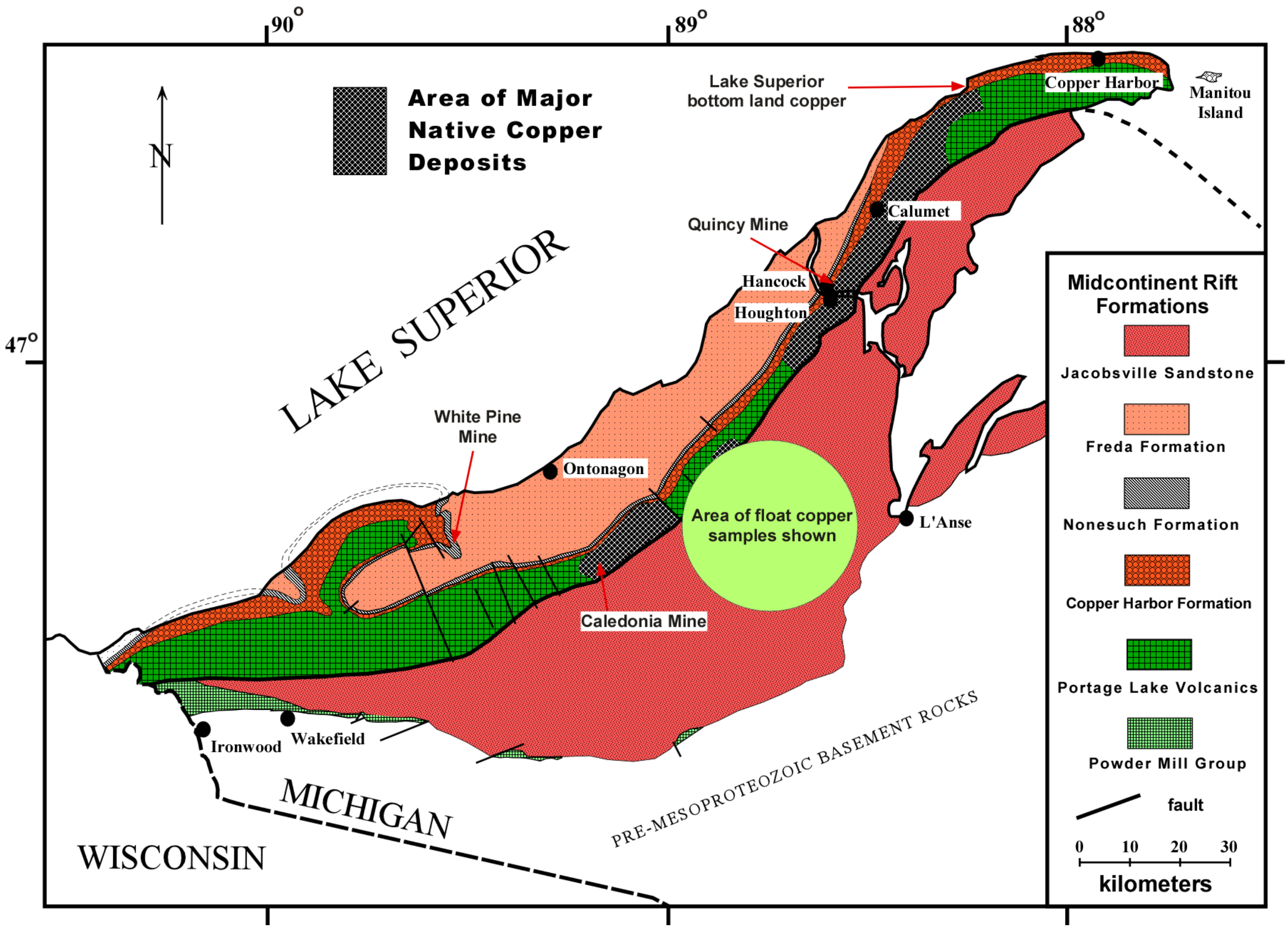

Figure 1. Geological map of Keweenaw peninsula [modified from 5].

Lake Superior bottomlands copper (relevant for 10000 year time frame) occurs as various masses of native copper on the bottomlands of Lake Superior being under fresh lake water since the retreat of the glaciers 10,000 years ago. These masses have been exposed to oxic to anoxic surface water.

Excavated copper (relevant for 50-150 year to present time frames) occurs in waste rock piles left by mining (Fig. 3). Large masses of native copper could only be removed from the mines in the 1800s by hand chiseling slots through them. The chisel chips (archeological artefacts) in the waste rocks piles were once pure native copper that have been exposed to unsaturated oxic groundwater.

These occurrences provide a unique chance to investigate copper corrosion in a variety of environmental settings. The resulting data will significantly increase our quantitative and qualitative understanding of the long-term corrosion of copper. This information used together with experimental results and corrosion modeling can help to optimize repository designs and provide alternative line of evidence for more realistic estimates of copper corrosion.

Figure 2. Cut slab from a mass of float copper from Quaternary deposit showing a thin layer of surface alteration on surface and silicate inclusions.

Figure 3. Chisel chips carved by miners showing surface oxidation after exposure for approximately 150 years.

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More realistic treatment of long-term cement degradation: support from ancient natural cements

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I. Overview

Recently, national regulators have been calling for a less conservative approach to the assessment of engineered barrier degradation: for example, in 2009, the Swedish regulator, SSM, noted that it would like to see the long-term degradation of cementitious materials (waste, containers, backfill, tunnel liners) treated in a more realistic manner.
Current treatment is highly simplistic in most national programmes, utilising simple mixing tank approaches with emphasis on over-prediction of consequences (i.e. relatively rapid degradation of the cement leading to release of radionuclides to the surrounding host rock). Even when more sophisticated reactive transport codes are used for these assessments, they are generally supported by only short-term laboratory experiments, so it is perhaps not surprising that longer-term processes are treated in an over-conservative manner (due to a lack of relevant data). Clearly, additional support is required from examination of very old natural cement systems such as found in Jordan (2 Ma) and Northern Ireland (58 Ma; see [1] for details).

II. Focus on realistic degradation of cementitious materials

Most assessments of long-term concrete degradation to date focus on leaching of the cement, with concomitant loss of the flow barrier and loss of the radionuclide retardation capacity of the material. However, this approach ignores the fact that:

- very old cements exist: e.g. Scawt Hill in Northern Ireland (Figure 1) is ca. 58 Ma old [2]
- they are very widespread: e.g. the natural cements in North Africa[1] cover an area of around 500,000 km^2

suggesting that this approach is fundamentally flawed.

III. Proposed approach

A. *Introduction*

The approach proposed here is to examine evidence of long-term sealing of cementitious materials. Although sealing processes such as carbonation and ettringite development can be viewed as mainly favourable phenomena in a safety assessment (SA), they have generally been neglected to date (see comments in, for example, [3, 4]), once again, due to a lack of relevant data on the long-term evolution of cementitious materials. In both the examples noted above (i.e. Northern Ireland and North Africa), the natural cements are effectively impermeable and remain unchanged until accessed by groundwaters (through tectonic damage, for example). However, even then, the tendency is for water pathways in the cement system to re-seal (e.g. Figure 2) following disturbance, with secondary $CaO–SiO_2–H_2O$ (CSH) phases [e.g. 2], carbonates following carbonation reactions [e.g. 5] and sulphates following reaction with groundwater sulphate [e.g. 6].

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[1] They stretch from Syria in the north through Israel and Jordan and on down to Saudi Arabia in the south.

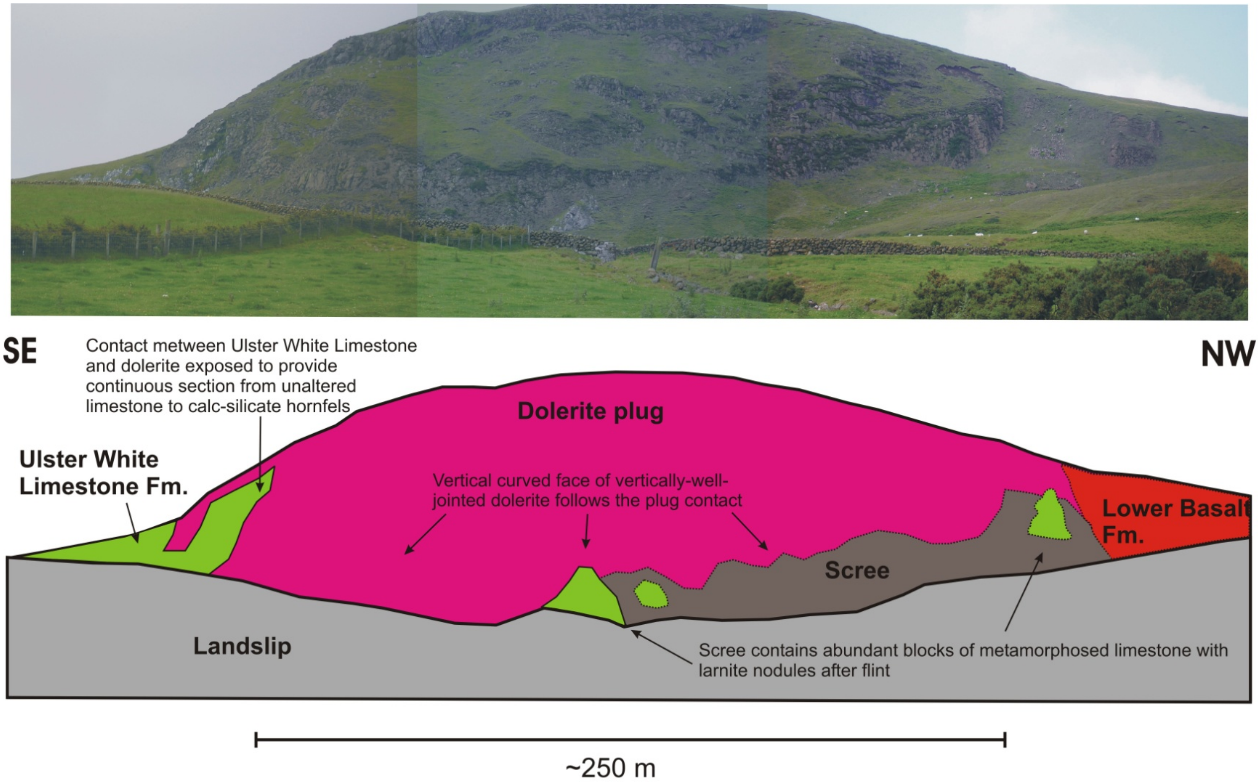

Figure 1: The Scawt Hill site in Northern Ireland (top). The natural cements are in the contact zone between the Ulster White Limestone and the dolerite plug (bottom) [7]

B. *Details*

It is proposed to sample at several sites in the widespread Middle East natural cements as these have been extensively quarried in the past (so access and sampling is much easier) and have been studied in detail in both Jordan and Israel (see [8], for background information).

To provide direct input to today's generation of models, it is proposed that those parameters already identified in previous modelling studies [e.g. 9] are prioritised. To do this, samples from sealed fractures, fracture associated cement and the cement matrix (cf. Figure 2) will be collected and analysed for:

- mineralogy – to identify primary and secondary mineral phases
- porosity – to identify changes in the original cement pore spaces due to reaction
- permeability - to identify changes in the original cement and fracture faces due to reaction and to assess how these values compare with those used in current models and SA
- diffusion rates - to identify changes in the original cement and fracture faces due to reaction and to assess how these values compare with those used in current models and SA
- stable and radioactive isotopes to provide a mechanistic understanding of the changes – for example, δ13C can identify sites of carbonation, δ34S can identify sites of ettringite/thaumasite pore blocking, natural decay series can provide times of reaction etc.

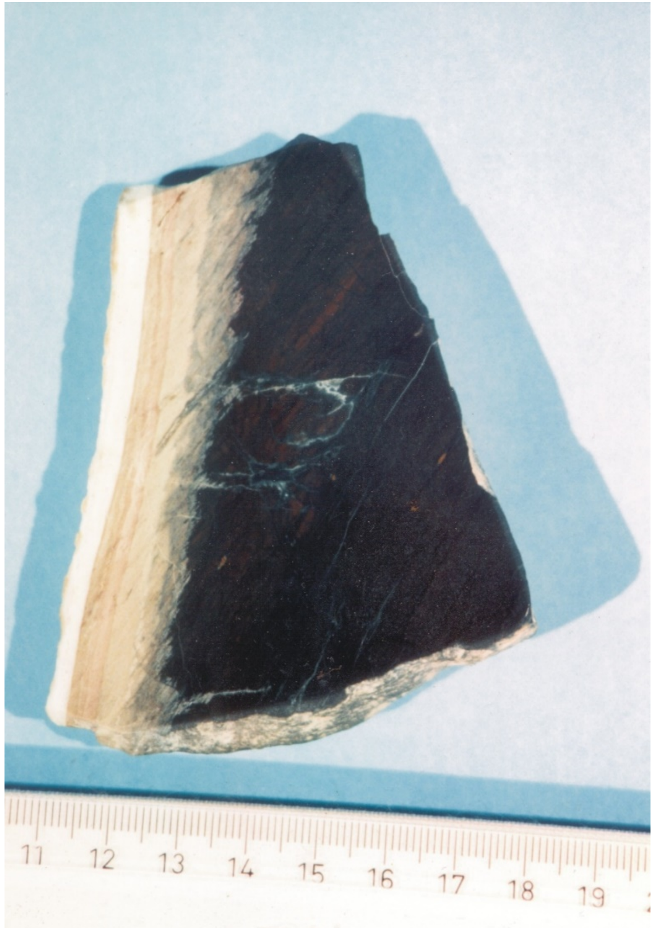

Figure 1: a typical re-sealed fracture in a natural cement from Daba, central Jordan. The white zone on the left of the sample is a sealed fracture and the creamy areas in the black cement host rock represent reaction fronts penetrating the cement
(Image courtesy H.A. Alexander)

IV. Output

Two main items will be provided:

- The first clear, mechanistic understanding of repository-relevant, long-term degradation of cementitious materials. This should include materials covering:
  - a range of palaeo-environments (as found in Jordan, for example, see [8]) to cover a range of original cement mineralogies and densities, groundwater flow and cement degradation scenarios
  - a range of flow system ages and time since sealing (and/or re-sealing in tectonically active zones) of the cementitious material may be relatively fast in some host rocks and slow in others
  - zones where groundwater transport has been in fractures in the cement (e.g. in the Daba area of Jordan) and other zones where groundwater transport appears to have been diffusive (e.g. the Khushaym Matruk area of Jordan)
  - if possible, where gas may have occurred
  - as both the rates of sealing and depth of matrix infiltration are important parameters for coupled transport model testing, these will be addressed with particular care

- A fully detailed test case for coupled transport codes which aim to model long-term degradation of cementitious materials

Finally, although this document has focussed on examples of natural OPC (Ordinary Portland Cement), it is worth noting that numerous examples of archaeological analogues of low alkali cements have now been examined (e.g. Figure 3). Although these studies are obviously of much younger concretes than those natural OPCs noted above, there are clear indications of concrete longevity over periods of several thousand years (see overview in [10]). In addition, sites where natural materials which are analogous to low alkali cements exist and, as noted in [11], these could be accessed in the future to assess truly long-term behavior of ancient low alkali cements in a similar manner to that outlined above for natural OPC.

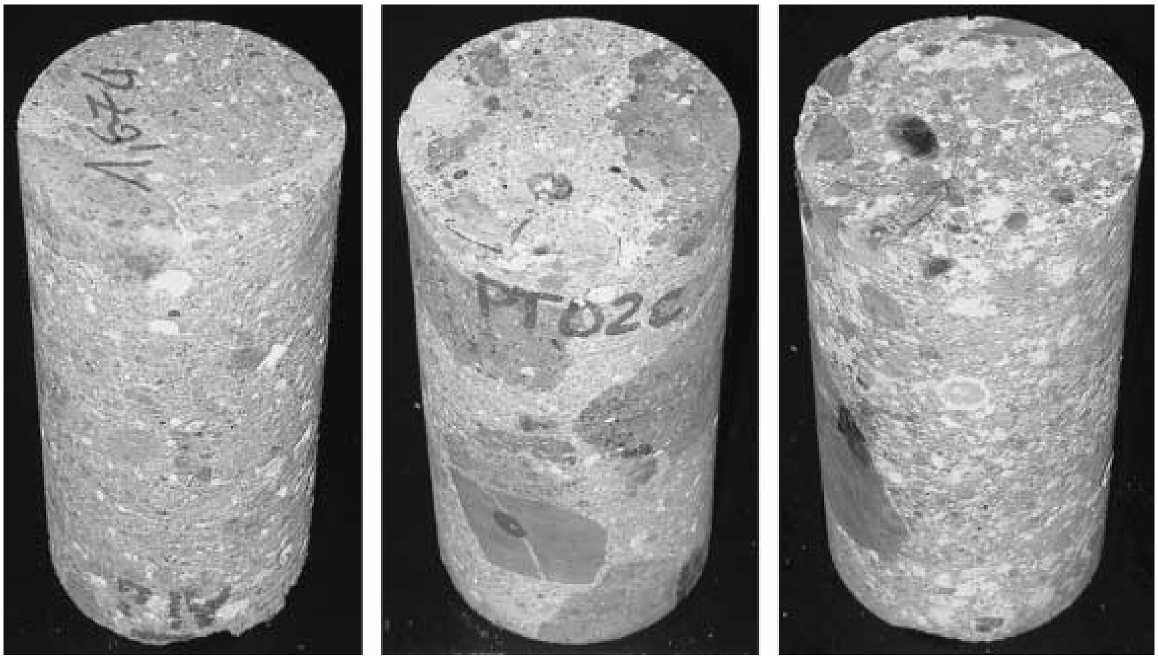

Figure 3: Typical low alkali cement core samples recovered from archaeological sites at Portus and Anzio, Italy [12]

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The oldest steel in the world? A first look

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I. OVERVIEW

The main perturbations associated with massive steel canisters are failure through corrosion, hydrogen gas production due to anaerobic corrosion and redox changes around the canister following canister failure [1, 2]. As a check on the long-term performance of the canister, in the 1990s, both Nagra and JNC (now JAEA) carried out natural and archaeological analogue studies of iron artefacts from a range of environments (Figure 1).

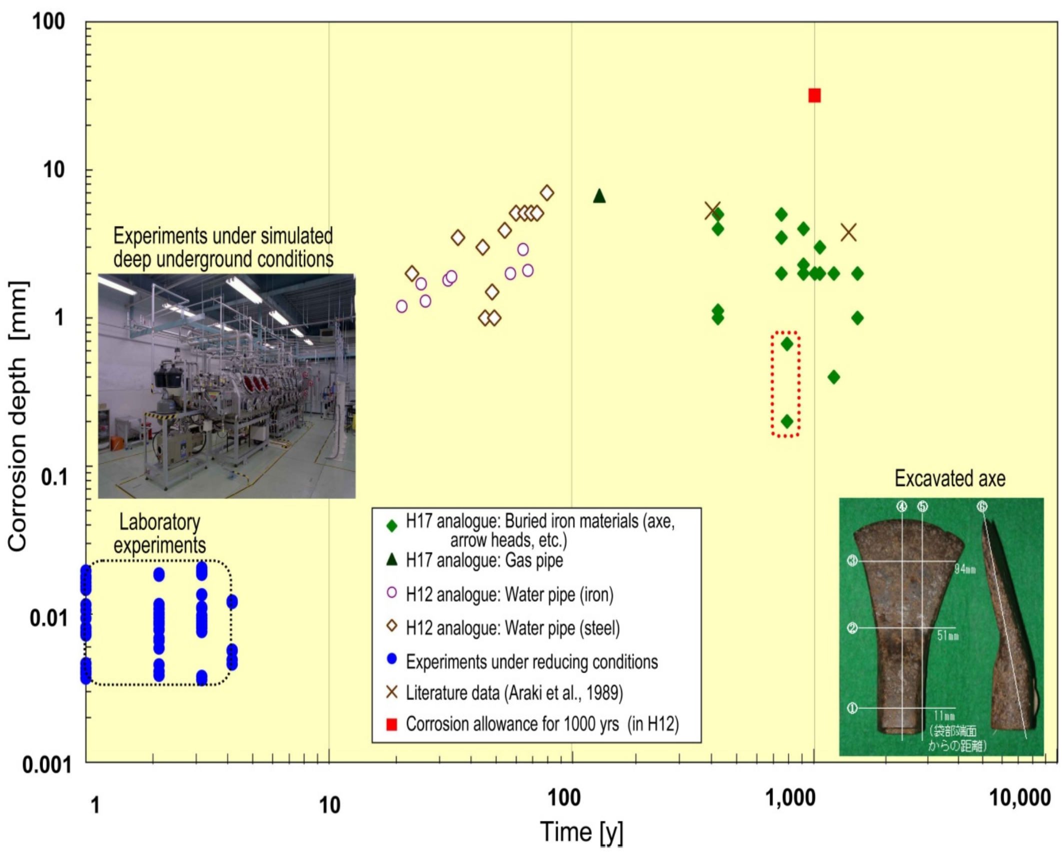

Figure 1: Integration of iron/steel corrosion data from laboratory experiments and several natural analogue sources (details in [3]). Note that the H17 analogues surrounded by the red dots are believed to have come from an aerobic environment.

Despite the fact that most material studied came from oxic to sub-oxic environments and would therefore be expected to corrode to a much greater extent than in the oxygen-free repository setting, a maximum corrosion depth of 10 mm in 1 ka was calculated by Nagra, so increasing confidence in the results from the short-term experimental data and the safety assessment (SA) Base Case assumption of 29 mm (Table 1).

Table 1. Comparison of steel corrosion depths cited in the H12 [2], Kristallin-1 [1] and H17 [3] safety assessments with a range of archaeological analogue data for steel/iron artefacts

Form of data	**Corrosion depth (per 1000 a)**	**Reference**	**Comments**
Short-term lab	31.8 mm	[2]	Uniform corrosion of carbon steel. Base Case value
Short-term lab	29 mm	[4]	Conservative corrosion rate, including an allowance for pitting. Base Case value
Natural analogue	0.09×10^{-3} mm	[5, 6]	Weathering of native iron in basalt (Disko Island)
Archaeological analogue	10 mm	Range of studies cited in [1]	Uniform corrosion of iron and steel
Archaeological analogue	<15 mm	Range of studies cited in [2]	Uniform corrosion of iron and steel
Archaeological analogue	0.1 - 10	[7]	Literature review of corrosion of archaeological samples
Archaeological analogue	<10 mm	Range of studies cited in [3]	Uniform corrosion of iron and steel

The first indications of iron use come from Ancient Egypt and Sumer where, around 6 ka ago, small items, such as the tips of spears and ornaments, were being fashioned from iron recovered from meteorites [8]. The oldest known samples of iron that appear to have been smelted from iron oxides are small lumps found at copper-smelting sites on the Sinai Peninsula, dated to about 5 ka ago[1]. However, although it would therefore appear possible to look at older iron artefacts, so strengthening the case for the use of steel canisters, the analogy arguably remains weak insofar that the archaeological materials are iron and not steel.

II. But what about steel?

Forms of steel were being made in China around 2.3 ka ago [8] and high quality steels reportedly first appeared in Sri Lanka by 2.2 ka ago [9]. More recently, steel artefacts have been reported from an Iron Age settlement in Scotland which was occupied between 2.2-2.8 ka ago [10], making these possibly the oldest steel material found to date. Broxmouth Hillfort (Figure 2) was excavated in the 1970s as part of a rescue dig before a cement factory was built on the site.

[1] Some iron oxides are effective fluxes for copper smelting, so it is possible that small amounts of metallic iron were made as a by-product of copper and bronze production throughout the Bronze Age.

Figure 2: aerial view of the Broxmouth Hillfort, Scotland [10]

Unfortunately, resources available at the time were limited so full analysis of the material collected took several decades and final reporting only occurred in 2013 [10]. As part of a 2008 re-examination of the findings at Broxmouth, new analysis of some metal artefacts (Figure 3), it was found that they can be dated to 2.4 – 2.5 ka ago. A range of steel artefacts have been analysed[2], including:

- jewellery (e.g. rings, brooches, cloak pins)
- metal bars and wires (to be reworked elsewhere)
- tools (e.g. tangs, punches, handles)
- weapons (e.g. spear ends)
- fittings (e.g. nails, tacks, staples)

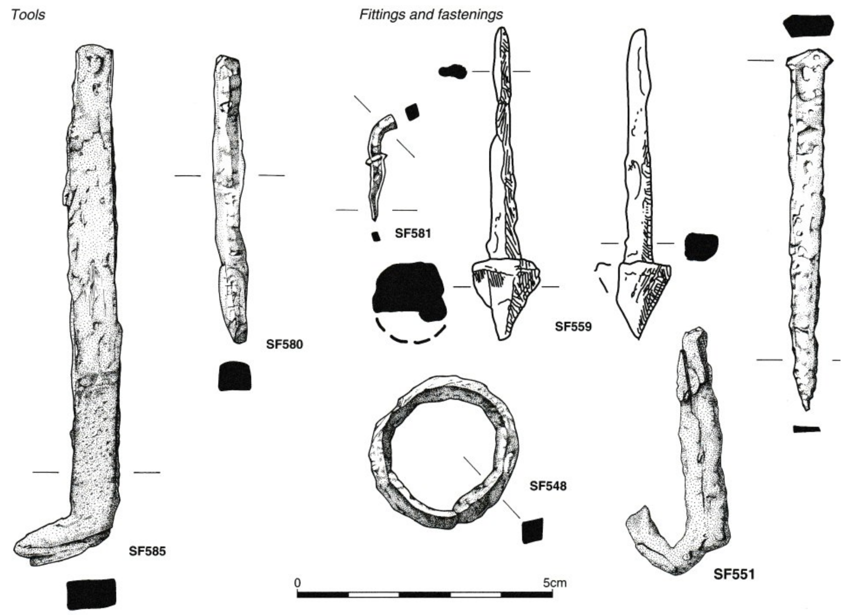

Figure 3: examples of the steel and iron artefacts from the Broxmouth Hillfort, Scotland [10]

The artefacts were collected from a range of environments, including:

- house post holes
- defensive ditches
- middens
- fort entrance gates
- roadways

and from a range of ages across the period of occupation of the site. An example steel artefact, made from high carbon steel which has been heat-treated and quenched, is shown in Figure 4. The unetched image (4A) is clean metal with little slag and, as can be seen in image 4B, where present, the slag inclusions have corroded significantly.

[2] But note, it is stated in [10] that "The selected artefacts (for analysis) were among the best-preserved objects in the assemblage…" and so there has clearly been a significant degree of bias in the sample selection.

Figure 4: an example of the steel artefacts identified at the Broxmouth Hillfort site (A unetched, B etched). Sample is 19.5 x 5.5 mm [10]

Currently, the steel artefacts recovered from the site of the Broxmouth Hillfort in Scotland have been only superficially characterised and, while their significance of these ancient metallurgical practices has barely registered in the archaeological community, it has caught the imagination of the UK public at least (e.g. [11]). Nevertheless, these artefacts are the earliest evidence of sophisticated blacksmithing skills in the UK – and would appear to represent the oldest known steel in the world. As such, their potential significance for offering both technical support to those repository concepts which utilise steel for canisters or containers and as evidence of steel longevity for stakeholder communication purposes should not be overlooked. Surely the oldest steels in the world deserve a second look – don't you agree?

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The use of natural, industrial and archaeological analogues in support of deep borehole seal design

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I. Overview

The results presented here are from one of the tasks undertaken as part of a multi-year project [1] to develop generic approaches to seal deep boreholes (BH) drilled as part of site investigations at a potential repository site[1] in the UK. The seals should provide resistance against groundwater flow and gas migration, thus limiting the potential for radionuclide transport, in a range of geological settings of relevance for a future UK repository. RWM (Radioactive Waste Management Ltd) is undertaking RD&D (research, development & demonstration) into BH sealing because they expect that the Initial Site Evaluation (ISE)[2] will require a clear description, supported by reference to RD&D and technology demonstrations, of how site investigation boreholes might be sealed

In most instances, borehole sealing systems comprise a combination of 'seals' and 'supports' (Figure 1). In addition, short deformable metallic bridge plugs could potentially be used for a variety of purposes in the borehole. The role of the seal is obvious, but the supports perhaps less so: for the overlying seal, the support element provides mechanical support in order to prevent the seal being damaged by movement within the borehole and, for the underlying seal, confinement. In the UK programme, it is envisaged that supports will be required in three environments:

- at locations where higher transmissivity features, such as fracture zones or permeable interbeds in the host rock, intersect the borehole. Such features are of limited vertical extent in the borehole, and could occur in both the host rock and any cover (overlying) rocks
- in intervals where lower permeability rock intersect the borehole. This might be sections of the repository host rock that do not require sealing or sections of the overlying or underlying rocks
- in intervals where higher permeability rock units intersect the borehole. This could occur in sections of rocks overlying or underlying the repository host rock. By definition [see 1], extensive sections of high permeability rock will not occur within the repository host rock

II. Approach

The work discussed here [2, 3] concerns the use of information provided from studies of natural, industrial and archaeological analogues (NA) to support generic designs for borehole seals (and seal supports) by assessing the likely long-term[3] behaviour of the materials of interest. It is of note that there is no research reported in the open literature relating directly to NA of borehole seals[4], but general information on the behaviour and properties of relevant materials does exist and this has been assessed with the aim of extracting data of relevance to the project. Information on the longevity of a range of materials relevant to borehole seals and seal supports has been examined, with the focus on:

- bentonite and bentonite/filler material mixes
- cements and concretes (both OPC and low alkali cements)
- a few other materials of potential use such as baryte

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[1] Also known as a Geological Disposal Facility (GDF) in the UK programme.

[2] The ISE in the UK refers to a document which will be submitted by RWM to the UK Environment Agency as part of the process to obtain permission to start surface-based intrusive investigations. Although the requirements are not yet fully defined, RWM expects that it will require a clear description, supported by reference to RD&D and technology demonstrations, of how future site investigation boreholes might be sealed.

[3] In the context of the UK programme on BH sealing, long-term may be taken to extend to 1 million years after repository closure (the time period typically considered in the post-closure Environmental Safety Case).

[4] Although some work does exist on NA of tunnel and shaft seals [e.g. 4] and this is reflected here.

The key issues for generic research into BH sealing were identified as:

- to determine the functional requirements of BH seals
- to determine the standard of sealing that is likely to be required from the BH seal, recognising that there will be uncertainties at the current generic stage in the UK programme
- to determine the most appropriate seal concept and emplacement method for each generic geological environment and to evaluate the advantages, disadvantages and risks associated with the different sealing concepts
- to identify how the quality of the emplaced seals and support elements can be assured
- to identify appropriate materials for post-closure support elements, taking into account both mechanical stability and chemical interactions with adjacent seals.

The results reported in [2, 3] on a wide range of aspects related to the longevity of BH seals and supports should be viewed within this context.

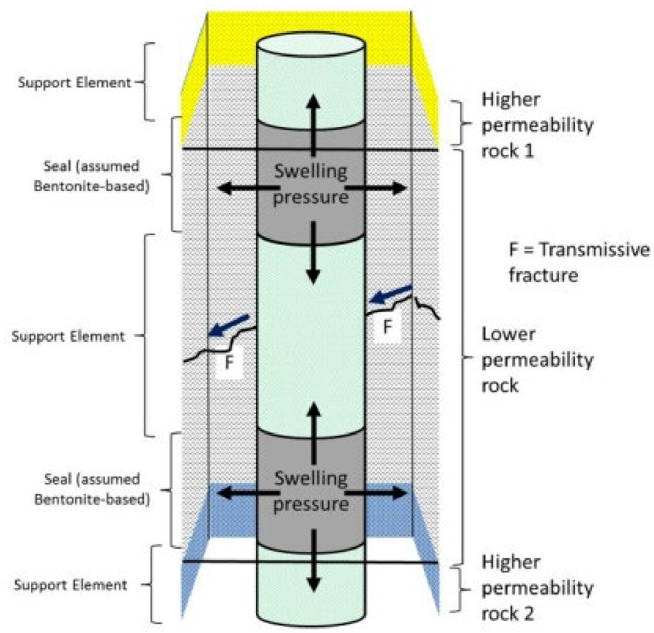

Figure 1: Schematic illustration of a section of borehole showing a potential arrangement of seals and support elements [1]. In this example, seals are located within the lower permeability rock. A support element is placed across a high transmissivity fracture within the low permeability rock and in the adjacent higher permeability rocks

III. Results

As this is a novel area for the application of NA data, several gaps in the literature have been identified and, where appropriate, issues that could be explored in the future have been assessed. The main results indicate that specific NA information which is targeted at borehole sealing *per se* is all but missing. Nevertheless, sufficient background information can be collected by data mining existing NA studies to provide qualitative support for many of the issues touched on in the project and, here, some examples are presented in Table 1 for bentonite seals[5]. Further, the reports note numerous examples where more can be supplied not only at a qualitative level, but also where truly quantitative support could be available. Such information would be produced through further NA studies (e.g. novel work in Italy and Jordan – see Table 1) or extending older work through re-analysis of existing raw data or existing samples or acquiring new material from an existing site (e.g. at the Kato Moni site in Cyprus – see Table 1).

[5] More information on the longevity other seal and support materials and relevant long-term processes can be found in [2, 3].

Table 1: main conclusions on the use of NA to support the longevity of deep borehole seals and supports: some examples of data of relevance for the longevity of bentonite seals

Materials/Processes	Area of interest	Examples of relevant NA data
Bentonite blocks	Can well-fitting blocks of highly compacted bentonite (dry density of 1,900 kg m^{-3}) provide an effective long-term seal against the borehole wall and seal supports after saturation?	Several bentonite quarries and mines where the bentonite is under a natural confining pressure provided by overlying formations [e.g. 5, 6] suggest yes and this could be assessed quantitatively (see discussion in [5])
Bentonite pellets	Will pellets provide a fully homogenous, long-term, effective seal?	Longevity and homogeneity currently unknown, but natural bentonite pellets in the Philippines [2] and Cyprus [6] could be assessed
Bentonite-OPC (Ordinary Portland Cement) interaction	Will the high pH (initially >13) cement leachates degrade the bentonite? If so, will any degradation impact the long-term behaviour of the bentonite?	Relevant NA studies are few and the current information is ambiguous [7] Khushaym Matruk in central Jordan would appear to be an appropriate site to study potential reaction [8]
Bentonite-low alkali cement interaction	Will the lower pH (9-11) cement leachates degrade the bentonite? If so, will any degradation impact the long-term behaviour of the bentonite?	Recent data from sites in Cyprus [9] and the Philippines [10] suggest reaction rates are too slow to significantly impact long-term bentonite properties
Bentonite-metal interaction	Will there be any long-term impact on bentonite properties from metal leaching and/or corrosion products?	For steel/iron material in the borehole, existing NA studies are not relevant enough, although general observations from natural systems [e.g. 11] suggest uptake of iron could reduce swelling pressures For copper, few NA data exist, but qualitative data from the Kronan cannon (see [12]) and the Littleham Cove copper-uranium concretions [13] are available and these could be more rigorously integrated with existing laboratory data (see discussion in [2])
Bentonite-(host)rock interaction	Due to the small volume of a bentonite borehole seal and the large relative surface area in contact with groundwater, it would be appropriate to confirm whether limited reactions at the seal – rock interface could impact the long-term seal performance	Little thought seems to have been given to bentonite-rock reaction *per se* in either the mainstream bentonite or NA literature. But limited information in [6] suggests it could happen and this will be studied as part of a new NA project [5]
Bentonite-groundwater interaction	Bentonite-groundwater interaction has been studied extensively [e.g. 1] with the focus on the impact on bentonite longevity due to interaction with: • low salinity groundwaters	For low salinity groundwaters, [14] noted that that there are no relevant NA studies, but a new study [5] will specifically examine this process For high salinities, qualitative data from a range of sites suggest this is

	• high salinity/brine groundwaters • high potassium groundwaters	not an issue, sites for bentonite-brine interactions have been identified [2] For high potassium groundwaters, qualitative data from a range of sites suggest this is not an issue and if quantitative data are required, sites have been identified [7]

IV. Conclusions

Despite the lack of existing NA data to directly support an assessment of the longevity of borehole seals and supports, sufficient information has been accrued to allow qualitative definition of a range of processes of relevance to the long-term behaviour of generic seal and support designs for the UK programme. In addition, sites where focussed novel data on seal and support longevity can be produced have been identified and could be examined in future if required, in contribution to the ISE.

V. Acknowledgements

The project (*Sealing of deep site investigation boreholes: Phase 2*) discussed here was funded by Radioactive Waste Management (UK) and undertaken by a team comprising of Amec Foster Wheeler (UK), Bedrock Geosciences (CH), Clay Technology (SE), Galson Science (UK), Nagra (CH), Schlumberger (UK) and Quintessa (UK). Phase 3 work is now underway.

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The use of natural analogues in building stakeholder confidence in Canada's plan for the long-term management of used nuclear fuel

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I. Introduction

The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally approved plan for safe long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

The physical composition of the used fuel itself, the repository, and its surroundings comprise a system that is designed to protect people and the environment through multiple barriers. These barriers include the ceramic used fuel, Zircaloy fuel element, long-lived corrosion-resistant containers, engineered sealing materials, and surrounding geosphere [1].

II. Canadian Multiple-Barrier System and Natural Analogues

The current conceptual design consists of a repository constructed at a nominal depth of 500 m below surface. The repository contains a network of placement rooms for the projected inventory of 5,224,000 used fuel bundles [2], encapsulated in about 108,800 long-lived used fuel containers.

The first barrier in the multiple-barrier system is the fuel pellet. Fuel pellets are made from uranium dioxide powder, baked in a furnace to produce a hard, high-density ceramic. Ceramics are extremely durable; they do not readily dissolve in water, and their resistance to wear and high temperatures make them one of the most durable engineered materials.

Each fuel bundle is composed of a number of sealed tubes called fuel elements (see Figure 1). Fuel elements contain the fuel pellets and are made of a strong, corrosion-resistant metal called Zircaloy. Zircaloy is the second barrier in the multiple-barrier system.

For the third barrier, used fuel bundles will be placed into large, very durable containers (see Figure 2). The Canadian container design is optimized for the used CANDU® fuel produced by Canadian nuclear power reactors. The steel inner shell provides strength to resist the local pressure underground, the bentonite swelling pressure, and the pressure from future glaciations. The copper coating provides corrosion protection of the inner shell [3].

Bentonite clay is the fourth barrier. It is a natural material proven to be a powerful barrier to water flow; it swells when exposed to water, making it an excellent sealing material. Bentonite is also very stable, as seen in natural formations formed millions to hundreds of millions of years ago. During placement in the repository, each used fuel container will be encased in a highly compacted bentonite clay buffer box (see Figure 3). Highly compacted bentonite will be used to fill all open spaces in each placement room and to seal the room entrance.

The repository will be approximately 500 metres underground – the exact depth will depend on the site. It will be excavated within a crystalline or sedimentary rock formation that meets the safety and technical requirements of the project. The enclosing geosphere will provide a natural barrier that is hydrogeologically, geomechanically and geochemically stable on postclosure timeframes; also, it will have low permeability, which means there will be little groundwater movement. The geosphere is the fifth barrier in the multiple-barrier system and will protect the repository from disruptive natural events, water flow, and human intrusion.

Long-term repository performance cannot be verified by experiment over relevant time scales. Natural analogues are natural features (materials or processes) that are similar to those expected in some parts of a deep geological repository. They illustrate long-term behaviour and can assist in understanding how a repository may behave over time scales ranging up to many millions of years, including the underlying principles relevant to the long-term isolation and containment of used nuclear fuel. They provide support for key model assumptions and for the identification of processes that need to be represented and those that can be excluded.

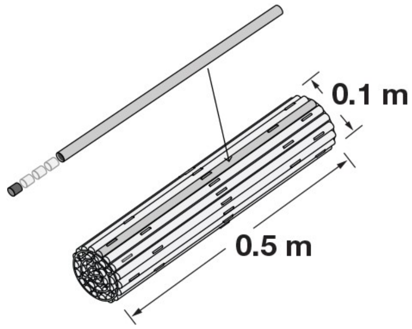

Figure 1. Used nuclear fuel is contained within Zircaloy fuel elements.

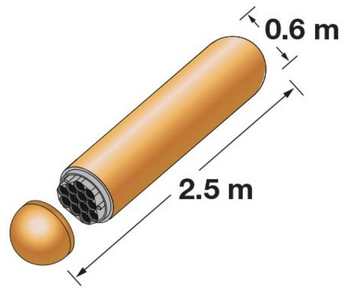

Figure 2. Containers are designed to isolate used fuel in a deep geological repository, essentially indefinitely.

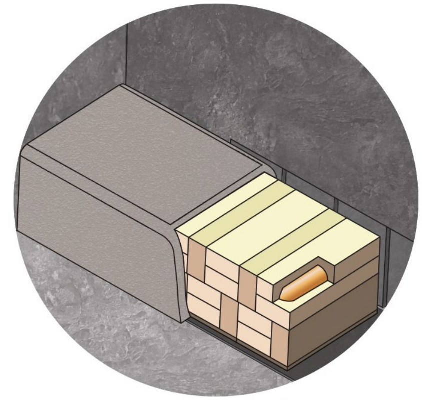

Figure 3. Bentonite clay is a very stable material formed millions of years ago.

Natural analogues exist for most features of the repository system, including the used fuel, engineered and natural barrier systems, and key processes such as transport of hypothetical contaminants. The use of natural analogues in supporting key assumptions in safety assessment and adding credibility to its findings is recommended in Regulatory Guide G-320 [4]. G-320 states: “Natural analogue information should be used to build confidence that the system will perform as predicted by demonstrating that natural processes will limit the long-term release of contaminants to the biosphere to levels well below target criteria.”

The Cigar Lake uranium deposit is located about 430 m below surface, similar in depth to the current Canadian repository concept. The uranium is primarily in the form of uranium dioxide, so is similar in general composition to used fuel. The ore is also very rich in uranium, with much of the ore body at around 20% uranium and portions even higher. The total amount of uranium is roughly comparable to that to be placed in a Canadian repository. Also, the ore is surrounded by a clay envelope somewhat similar to the clay buffer specified in the repository design. It can be considered analogous to a “worst case” simulation, as it lacks any analogue for the used fuel containers, and the host rock above the ore body is highly permeable sandstone.

Studies of the Cigar Lake ore body [5] conclude that uranium dioxide remained stable over 100 million year time scales under chemically-reducing conditions, with very little uranium migrating from the deposit; also, that the natural clay surrounding the ore provided a long-term seal, preventing migration of radionuclides from the deposit; and, that dissolved organic matter in groundwater migrating past the ore did not play a significant role in mobilizing radionuclides from the deposit. Insufficient radionuclide migration has occurred around Cigar Lake to produce any detectible concentration anomalies in the soil, surface water and lake sediments and waters overlying the ore body.

Copper is one of the relatively few metals that naturally occurs in their metallic state, indicating that it is stable under geological conditions. Deposits of metallic copper provide a natural analogue for estimating the longevity of copper-coated used fuel containers. Copper “plates” found in the mudstones from South Devon in England provide a natural analogue for the corrosion of used fuel containers placed in a clay backfill – the plates were formed 200 million years ago and show little corrosion since that time, due in part to the protection of the clay-rich mudstone [6]. The Keweenaw Peninsula of Michigan hosts the largest known deposit of metallic copper, where large pieces were either mined or found in glacial outwash. Data from these natural coppers help bound long-term copper corrosion rates for both reducing and oxidizing environments, which are useful in assessing the longevity of the used fuel containers.

The Dunarobba Forest in Italy provides a natural analogue of the effectiveness of clays in minimizing groundwater movement [7]. The sequoia-like Dunarobba trees were buried in clay for 1.5 million years. The clay minimized the flow of water to the trees and prevented oxygen from reaching the wood. This maintained reducing conditions around the wood, protecting the wood from bacterial or fungal decay or chemical oxidation. As a result, the trees did not decay. They also did not fossilize - they are still made of wood.

Similar analogues have been found in the Canadian Arctic on Axel Heiberg Island [8] and at the Strathcona Fiord on Ellesmere Island [9], where shale deposits over 40 million years old were found to contain preserved specimens of redwood, walnut, elm, birch and alder; also, gingko and katsura, now native to eastern Asia. The shale, which is consolidated clay, provided an effective barrier to oxygen and preserved the wood such that the wood grain and bark are preserved without chemical alteration – the cellular structure and most of its molecular structure remain intact.

Natural analogues for the behavior of the geosphere are also available. The site itself is an important analogue for the future behaviour of the geosphere at the site; in particular, geoscientific evidence of the past history of the site provides a direct analogue for future behaviour. This will be gathered for the Canadian site as part of the characterization and assessment work.

III. Communicating the NWMO Safety Approach

The primary safety objective for the deep geological repository is the long-term containment and isolation of the used nuclear fuel. Safety assessment provides a quantitative evaluation of the overall performance of the repository system and its impact on people and on the environment. In doing so, it is also able to identify the key features or processes that contribute to confidence in long-term repository safety.

Assuming reasonable extrapolation of present-day site features includes the expected evolution of the site and expected degradation of the repository system. Normal evolution is described in terms of a “reference case” and a series of associated sensitivity studies. The reference case represents the situation in which all repository components meet their design specification and function as anticipated. As such, the used fuel containers remain intact essentially indefinitely and no contaminant releases occur in the one million year time period of interest to the safety assessment.

The associated sensitivity studies illustrate repository performance for a range of reasonably foreseeable deviations from key reference-case assumptions (see Figure 4). These deviations arise as a result of components unknowingly placed in the repository that either (a) do not meet their design specification or (b) do not fully function as anticipated.

The “base case” assumes a small number of containers are fabricated with sizeable defects in their copper coating, and that a smaller number of these off-specification containers escape detection by the quality assurance program and are unknowingly placed in the repository [1].

To further define the base case, a number of bounding assumptions are made to account for uncertainties. A “bounding assumption” is an assumption that results in a greater consequence than the entire range of uncertainty, usually at the expense of realism. It allows for complex problems to be reduced to much simpler ones, with the downside being that the resulting case is no longer the most realistic. While this is acceptable from a licensing viewpoint (provided results meet acceptance criteria), it can make repository performance appear to be much worse than it really is.

Specifically:

- A self-sufficient farming family is unknowingly living and growing their own food on top of the repository. In reality, given the small footprint, it is possible that no-one will be living in exactly this location. A greater distance means more opportunity for dilution and dispersion of hypothetical contaminants, leading to lower doses.
- The family uses a deep well to obtain their drinking water. Given that there are many surface water bodies in the Canadian Shield and south-western Ontario, it is possible that a well would not be used. Concentrations of hypothetical contaminants in streams and lakes would be much lower than in the well due to greater dilution.
- The drinking water well is assumed to be fairly deep, about 100 m. In reality, it is unlikely that a family would use such a deep well. Current practice is to use more shallow wells for drinking water. Shallow wells allow for lengthier contaminant transport times with associated increased dispersion and dilution in the geosphere.
- The drinking water well is assumed to be in the location that maximizes the uptake of contaminants escaping the repository. In reality, the well would be in a random location with respect to the hypothetical defective containers. Depending on where the well is actually located, it’s possible that no contaminants would be captured by the well.
- The defective containers are assumed to all be clustered in the location that results in the greatest possible contaminant transport to the well. While the defective containers are likely to be randomly distributed, clustering may occur following a temporary lapse of quality control. Even if the containers were clustered, the likelihood that they would be in the location that results in the greatest transport to the well would be low.

IV. Summary and Final Remarks

Performance of repositories cannot be verified by experiment for time scales relevant to their long-term safety. Natural analogues provide qualitative and quantitative illustrations of long term behaviour. While they do not prove that the performance of the various repository components will continue indefinitely, natural analogues provide supporting arguments and increase confidence in the long-term performance of the repository.

Safety assessment provides a quantitative evaluation of the overall performance of the repository system and identifies the key features or processes that contribute to confidence in long-term repository safety. The adoption of bounding assumptions allows for complex problems to be reduced to much simpler ones.

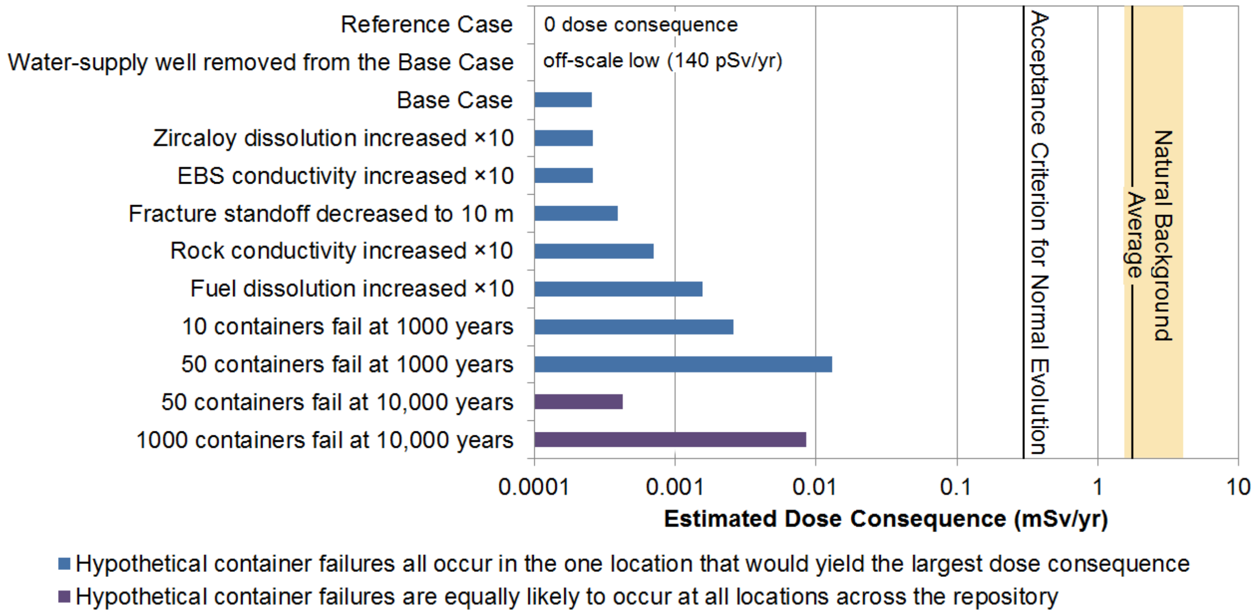

Figure 4. Radiological Dose Consequences for Sensitivity Studies.

As the site selection process continues, there are opportunities for the NWMO to learn from local, traditional knowledge. Indigenous knowledge places an emphasis on interrelationships within the environment and, as such, can offer insight into the overall repository system; for example, Indigenous societies have explored the copper deposits around the Great Lakes since before 3000 BCE [10] – these deposits present a natural analogue for the long-term durability of copper containers within the repository. The NWMO developed its Indigenous Knowledge Policy [11] to ensure decisions are guided by a clear set of principles, to recognize the role of Indigenous knowledge in the planning and development of the repository and to protect Indigenous rights to intellectual property.

Through the site selection process, the NWMO is building sustainable, long-term relationships with interested Canadians and the Indigenous peoples of Canada. This experience has illustrated that using natural analogues to support assessments of repository safety greatly helps to improve confidence that a deep geological repository is a safe and secure method for isolating used nuclear fuel from the environment.

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The Greenland Analogue Project (GAP)

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I. Overview

Deep geological disposal (DGR) of nuclear waste requires a multidisciplinary and iterative approach, to develop an overall scientific understanding of the long term performance of the repository and its surrounding. Given the long time span covered by safety assessments of DGRs for nuclear waste (100,000 years up to one million years), scientific information on processes related to cold climate conditions and future glaciations are required.

To increase this knowledge the Greenland Analogue Project (GAP) was initiated. The primary aims of the GAP were to enhance scientific understanding of glacial processes and their influence on both surface and subsurface environments relevant to the performance of DGRs for spent nuclear fuel in crystalline shield rock environment. The Greenland Ice Sheet (GrIS) was chosen as a natural analogue for future glaciations to occur in Fennoscandia and Canada over DGR safety-relevant time frames.

II. Outcome

The results and research undertaken as part of the GAP has advanced the scientific understanding of hydrological processes associated with a retreating ice sheet GrIS, including the temporal and spatial nature of processes occurring on the ice sheet surface (SPA), conditions at the ice sheet bed, thermal and meltwater generation (SPB) and also interactions between glacial meltwater and the underlying groundwater systems (SPC) (Fig.1) [1,2].

Hydrologic conditions at the ice sheet bed were found to vary across. Between the ice divide and the margin, there is evidence for three different basal zones as defined by the amount and configuration of meltwater: the frozen zone, the wet bed zone, and the active-drainage zone (Fig. 2). These zones result from surface, bed, and internal ice flow processes, and are likely representative of Northern Hemisphere ice sheets in a similar stage of development to the current GrIS [1,2].

The main part of the base of the ice sheet in the study area, including the marginal areas, has been shown to have basal melting conditions, with the exception of the central parts of the ice sheet. This, together with the glacial history of the region, suggests that permafrost does not exist under the major part of the large warm based areas of the ice, with the exception of the ice margin, where a wedge of permafrost most likely extends underneath the ice for some distance [1,2].

By applying the results from the GAP in future safety assessments, it will be i) possible to demonstrate a significantly increased process understanding within the fields studied, and ii) possible to reduce uncertainties in assumptions related to process understanding. Such demonstrations of process understanding are a cornerstone in safety assessment analyses for DGR of nuclear waste [1,2].

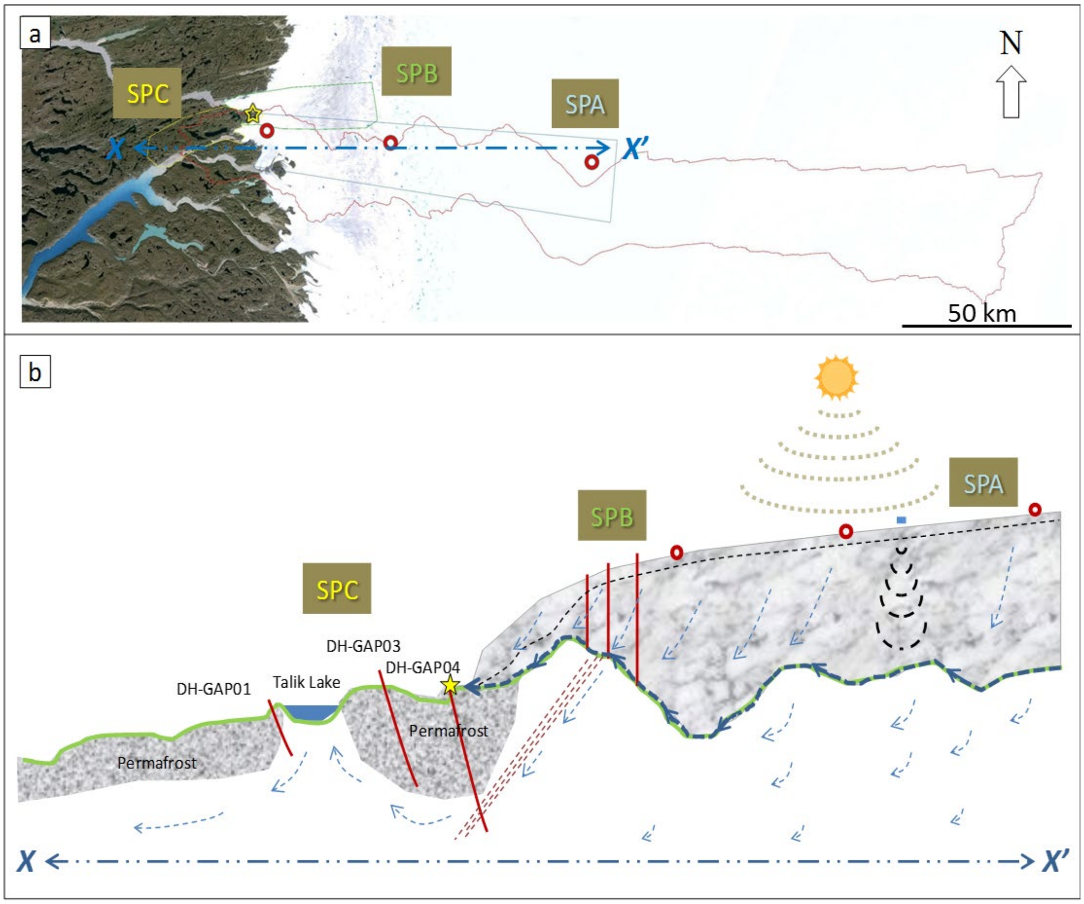

Figure 1. a) Map of the study area representing the three different research areas, SPA, SPB and SPC. b) Schematic picture representing the interaction between glacial surface meltwater, basal meltwater and the underlying groundwater systems. Modified picture from [1].

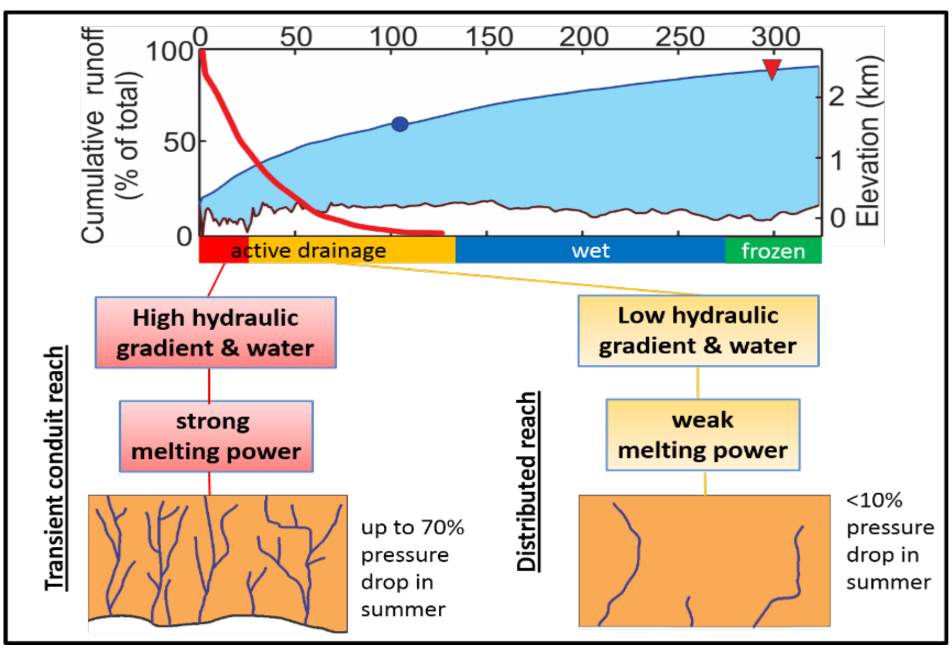

Figure 2. Between the ice divide and the margin, three different basal zones have been defined by the amount and configuration of meltwater; the frozen zone, the wet bed zone, and the active-drainage zone [1].

The GAP [1,2] has resulted in extensive amount of data and for the first time through observations it is possible to describe the following features:

- How pressure is varying through time and space underneath an ice sheet
- To what depth the meltwater is possible to penetrate into the bedrock in vicinity of an ice sheet
- What is the geochemical composition of the ground/meltwater in the bedrock underneath an ice sheet
- Groundwater formation underneath and in the vicinity of an ice sheet
- How an ice sheet impacts periglacial groundwater flow

III. Ongoing and Fututre Plans

Svensk Kärnbränslehantering (SKB) continues to maintain a few GAP-activities. The research borehole extending through the permafrost (DH-GAP04) will be maintained at least until 2020. The network of Automatic Weather Stations (AWS) on the ice sheet is also continuing to run until at least 2020, through cooperation with the Denmark and Greenland Geological Survey (GEUS).

An extension project was launched, when GAP finished in 2014, called the 'ICE' project where ice drilling through the GrIS was performed to study 'recharge'. The project is funded by SKB, Posiva, Nagra and NWMO and carried out by Univ. Montana and Univ. Wyoming, and is due to be completed in 2017.

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Stability of smectite under hyperalkaline fluids including Fe, Mg, Al ions

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I. Introduction

Significant amounts of cement materials will be used for the TRU[1] waste disposal system in Japan. The high pH cement leachate causes dissolution and alteration of smectite. As a result, bentonite may lose its favorable properties as a buffer material of EBS (engineered barrier system). Therefore, the long-term phenomenon of the hyperalkaline influence is a key issue of the safety assessment of waste disposal.

Hyperalkaline groundwater produced by serpentinization of ultramafic rocks in ophiolites is characterised by high pH, high Ca content and anoxic, that is, analogous to cement leachate. In this study, we show the alteration process under hypealkaline conditions by paying attention to dissolution/formation reactions by hyperalkaline fluid and mass balance of Fe, Mg, Si, Al, Ca in mineral formation and stability of smectite based on field survey in Palawan, SW Philippines and subsequent chemical and mineralogical analysis.

II. Natural Analogue Site

Many serpentinizing ophiolites are distributed in the Philippines. Palawan ophiolite in central~south Plawan is one of the typical ophiolites and the survey site for NA is Narra village, located in central Palawan. Hyperalkaline groundwaters at the site have been seeping into overlying clastic sediment (Fig. 1). We can accordingly estimate geochemical properties of hyperalkaline groundwater; pH>11, low Eh, 35-45°C and high Ca content, and reaction time; about 2,500-9,500 years by 14C dating for a carbonate, buried roots, shells and humic acid in the clastic sediment by JAEA-AMS-TONO. The reaction of the clayey clastic sediment with the hyperalkaline groundwater is here taken to be analoguous to the expected reaction between a clay buffer and the cementitious waste leachates in a TRU repository.

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[1] TRU: transuranic waste, more or less equivalent to L/ILW (low- and intermediate-level waste)

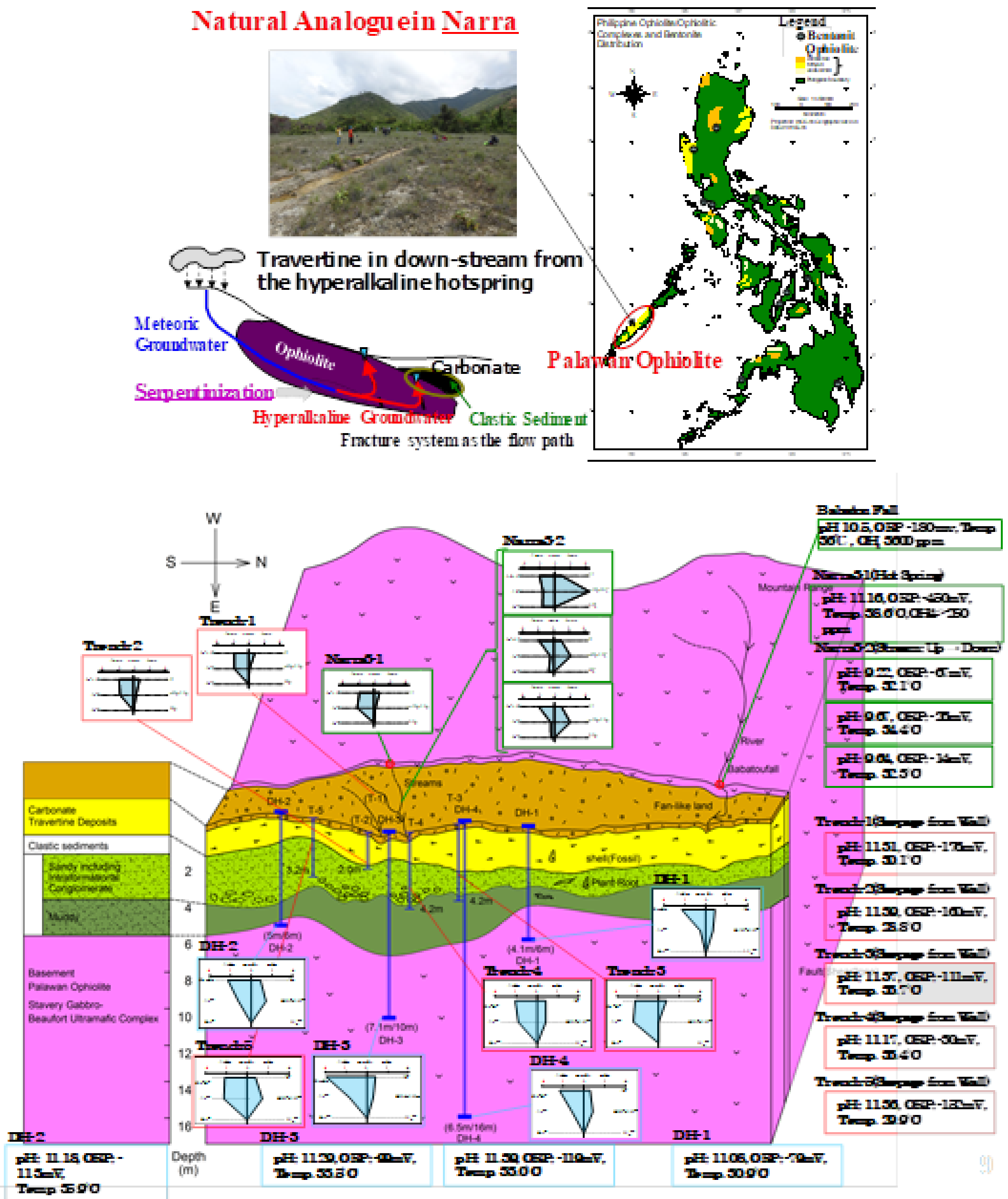

Figure 1: Overview of the geology and groundwater chemistry at the Narra site in the Philippines

III. Result and Discussion

The upper layer at the Narra NA site consists of widespread carbonate, mainly of calcite as travertine. The lower layer is consists of black clastic sediment and overlies the basement ultramafic rock of harzburgite. Samples taken from the clastic sediment in the trenches (trench 3~5 shown in Fig. 2) were analyzed by XRD, XRF and EPMA.

Smectite in the almost all clastic sediment was identified by the peak shift of single-crystal XRD pattern after ethylene glycol treatment. The (060) reflections of Powder XRD (Fig. 3) suggest that the smectites are of various types (e.g. di-octahedral type such as nontronite and tri-octahedral type such as saponite or stevensite). C-S-H phases were also seen to coprecipitate with saponite. This evidence suggests that saponite was precipitated from hyperalkaline groundwater by EPMA (Fig. 4).

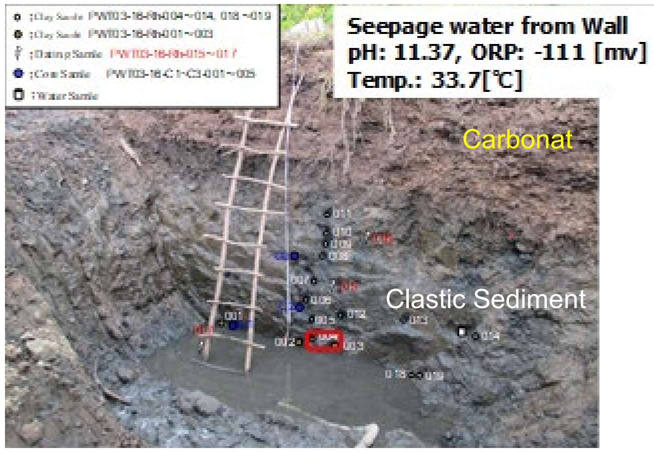

Figure 2: Surface of the wall and sampling points in trench3

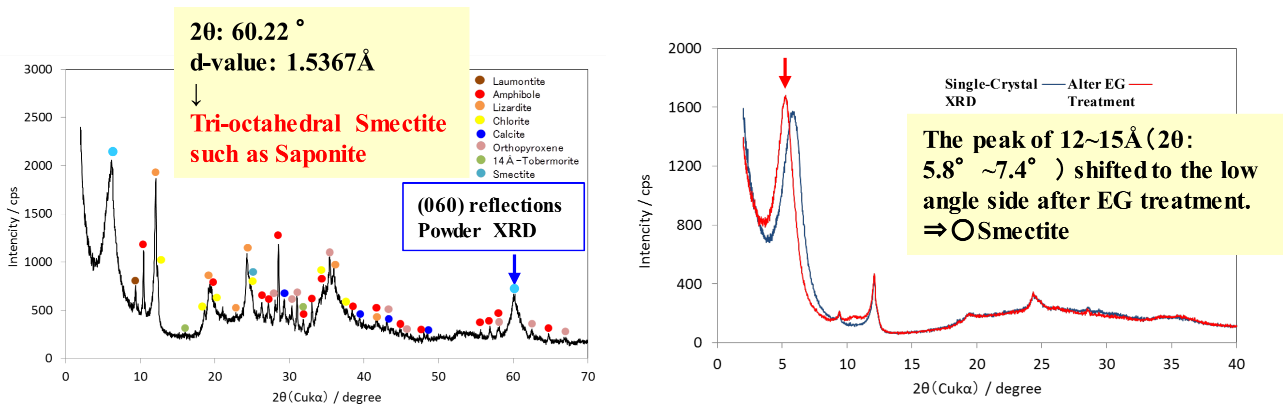

Figure 3: Powder XRD pattern (left figure) and Single-Crystal XRD pattern (right figure) of PWT03-16-Rh-004

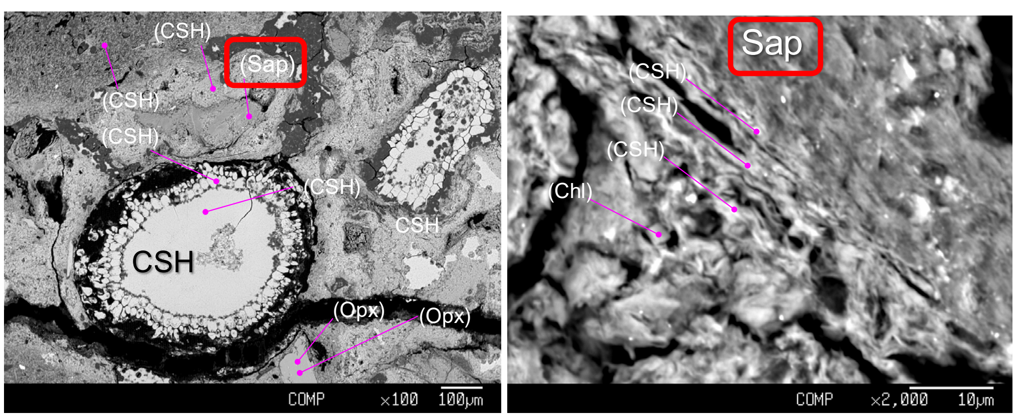

Figure 4: EPMA analysis suggests coprecipitation of C-S-H and saponite following reaction with the clay rich sediments

Fe, Mg, Si, Al and Ca in the hyperalkaline fluid affected the formation of smectite. The difference of the smectite formed under the conditions of different Al contents can be recognized by comparison of different trench samples. Saponite (including Fe-Saponite) were formed in every trenches, but steavensite were formed only on the Al-poor condition in trench-3/-4. One secondary mineral has the same chmical composition as sepiolite [1], which contains the same ribbons with a 2:1 type layer structure as the secondary palygorskite observed under similar conditions in Cyprus [2]. A part of the smectites in trench-5 were notronite.

Tectonic evolution of the Palawan ophiolite and smectite formation in clastic sediment can be explained as follows. The origin of the clastic sediments (Fig. 1) is the underlying ultramafic rocks (harzburgite and gabbroic dyke) of the Palawan ophiolite. The sediments were formed by erosion, transport and deposition of the weathered ultramafic rocks after the emplacement of the Palawan ophiolite (ca. 23-33 Ma*)[3]. The overlying travertine (carbonate precipitation) was formed by CO_2 uptake by the hyperalkaline fluids at the top of the clastic sediments.

While it is imposible to observe natural analogue of bentonite buffer system only at Narra site, because there is no bentonite and the smectite including in the clastic sediments is not montmorillonite, it is nevertheless possible to study several important reaction processes concerning alkaline alteration of bentonite in Narra as a natural analogue to the repository environment.

Evidence from the Narra site show that hyperalkaline fluids with Fe, Mg is preferable for the formation of smectite and the so formed smectite is stable under high pH conditions. The hyperalkaline reaction at Narra site can be seen in the alteration processes of bentonite at Saile mine in Luzon [4]. An overview of the various alkaline alteration processes observed in the Philippines to date is shown in Fig. 5.

The worst scenario is that montmorillonite alters to non-swelling minerals such as zeolite, chlorite and illite. In addition, results suggest that one type of smectite (montmorillonite) can alter to another type of smectite (saponite, nontronite etc) under reaction with hyperalkaline groundwaters rich in Fe and Mg, suggesting that reaction with hyperalkaline fluids will change the desirable functions of the bentonite very little.

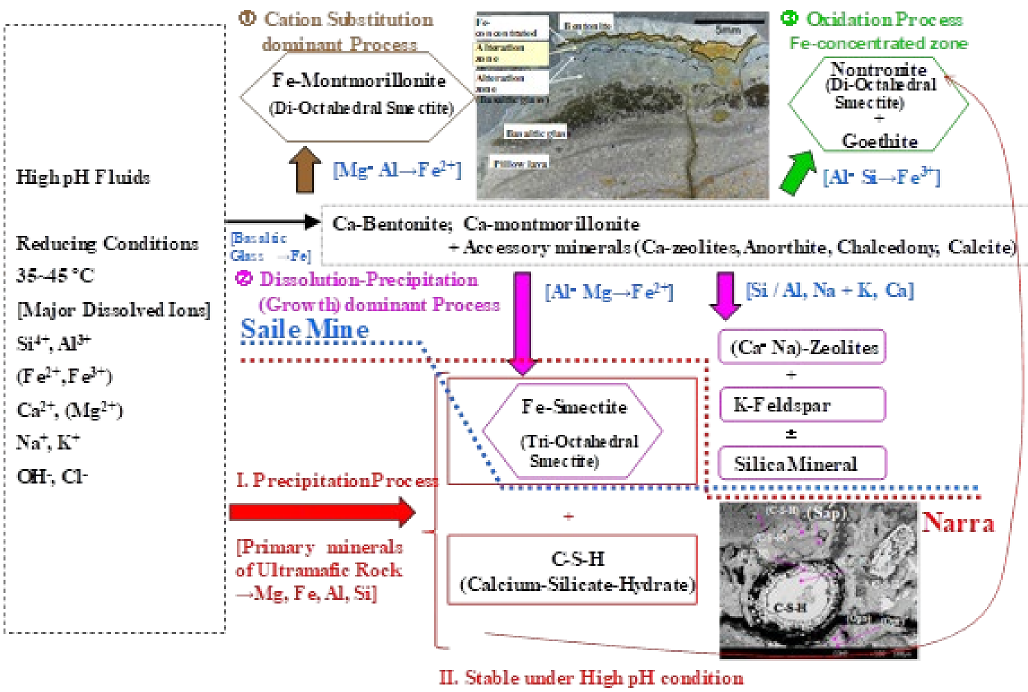

Figure 5: Overview of the various alkaline alteration processes observed in the Philippines

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Natural glasses as natural analogues for vitrified HLW

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I. Introduction

Czech republic does not consider spent nuclear fuel (SNF) reprocessing. However, 680 assemblies of highly enriched fuel from UJV research reactor was shipped into Russia (Mayak) within USA-RF-IAEA program (financed by USA) in 2007 and 2013. The goal of the project was to prevent the acquisition of nuclear and radiological materials for use in weapons of mass destruction and other acts of terrorism and encouraged eligible countries to convert their research reactors from high enriched uranium fued (HEU) to low enriched uranium (LEU)

Following that, several drums with phosphate borosilicate matrix fixed waste will be delivered back around 2022. The vitrified waste will be at the end disposed in deep geological repository (DGR). Therefore studies of waste glass matrix and it long term longevity is stil relevent even for the Czech national programme.

The presented review evaluated the role of analogues relevant to the long-term performance of vitrified high level waste (HLW), including the Czech concept .

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II. Glass analogues

Glass tends to slowly devitrify over time, albeit at a very slow rate. Evidence from such analogues shows that the mechanisms and rates of glass degradation depend both on the glass composition and the physical and chemical properties of the environment After evaluating the results of a large number of studies, it was found that several environmental parameters play an essential role in determining the long-term stability for all types of glass, namely:

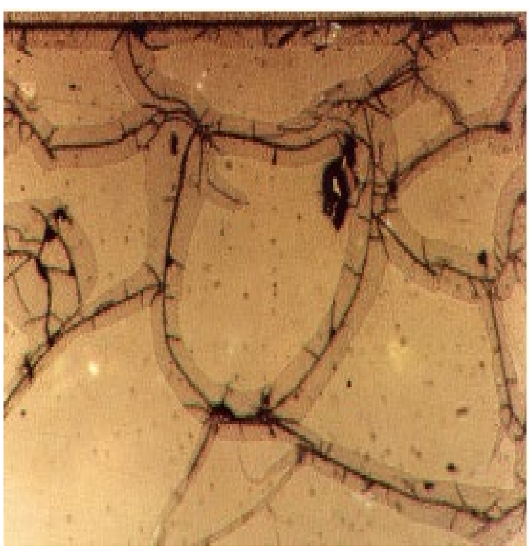

Figure 1. Altered surface of Bohemian uranium glass [1]

- temperature;
- pH;
- ratio of glass surface area to volume of solution (SA/V);
- water flux;
- glass composition (Si content);
- solution composition (Su concentration and alkali ions).

The identified processes that are the most important in the long-term behaviour of glass are following:

- dissolution (short term, in case of contact with water);
- devitrification (long time scales);
- leaching.

Examples of glass dissolution rates as one of the most important durability feature are presented in Table 1.

III. Glass long term durability

Basaltic glasses provide the best analogues to HLW waste, in terms of their composition, degradation processes, creation of a dehydrated layer and retention of trace metals within the material. In the laboratory, after initial ion exchange, the dissolution of basaltic glass becomes congruent until the production of secondary phases on the glass surface. Generally, these are aluminium and iron hydroxides followed by aluminosilicates when the silica activity increases [3].

Table.1 Examples of natural glass dissolution rates under different conditions [3] (references marked with *) are referred in [1])

Glass/solution	**Comments**	**Dissolution rate** (mol cm^{-2} s^{-1})	**Reference**
Basalt glass	Huallai Volcano (3kyr) 10–20 ºC	10^{-19} – $10^{-18.3}$	Gordon and Brady (2002)
Nepheline – syenite glass	Field rates (1 – 9 a)	$10^{-16.2}$ – $10^{-15.7}$	Melnyk et al., 1983*)
Nepheline – syenite glass	Lab rates (1 – 100 days)	$10^{-11.5}$ – $10^{-13.5}$	Melnyk et al., 1983*)
Basalt (minerals + glass)	10 ºC seawater rate estimated from measured activation energy and higher T rates	$10^{-14.8}$	Brady and Gislason, 1997*)
Basalt glass	25 ºC meteoric water, pH 9.4	$10^{-13.55}$	Gislason and Eugster, 1987*)
Basalt glass	25 ºC in seawater	$10^{-13.9}$	Crovisier et al., 1987
SiO_2	25 ºC	10^{-13} – 10^{-11}	Wirth and Gieskes, 1979*)
Various compositions	25 ºC	10^{-14} – 10^{-10}	Grambow et al., 1985*)
Glass phase of coal fly ash	25 ºC	10^{-12} – 10^{-10}	Yan and Neretnieks, 1995
Uranium glass	Soil, rain and groundwater	1,250 – 6,250 μm/1000a	Procházka et al. 2002a

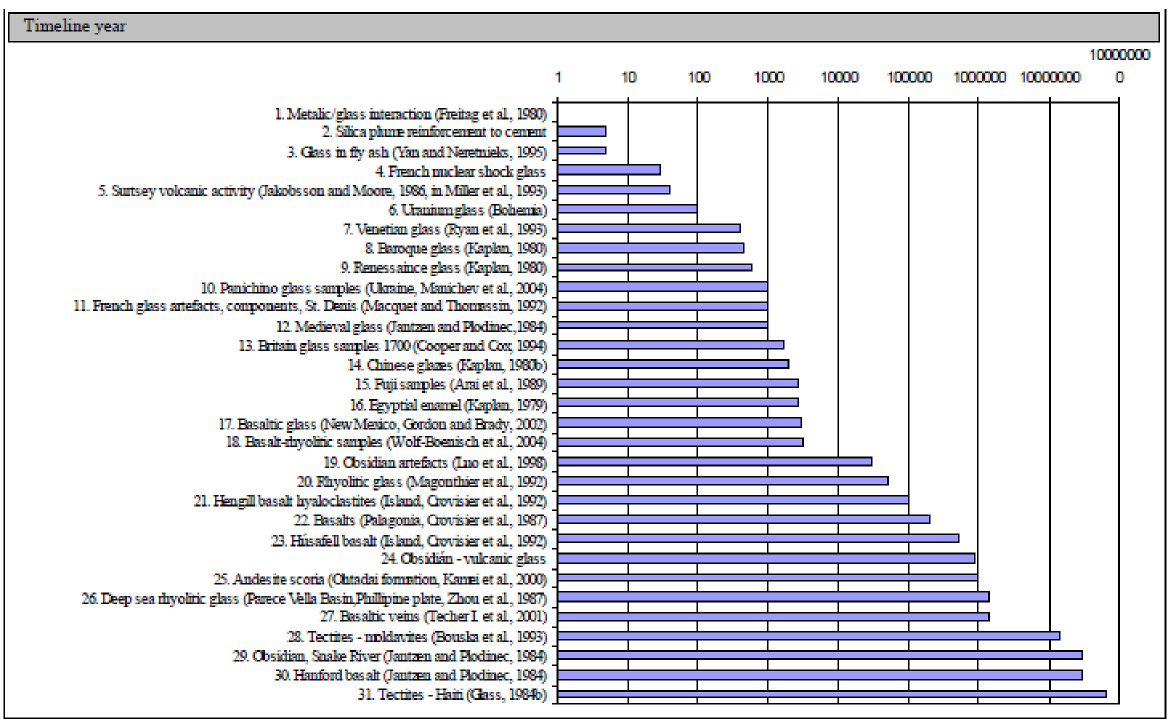

Figure 2. The timescales of the most representative glass analogues

The long-term durability of basaltic glass in natural environmental conditions has been clearly shown by analogue studies and although few volcanic glasses are older than 25 Ma several much older have been found (see Figure 2).

In natural systems, the first phases to form are generally termed palagonite. The palagonite is generally similar in morphology to the gel formed on vitrified HLW and seems to be formed by precipitation of minerals having reached their limit of solubility, following the congruent dissolution of glass. The next phases to appear are generally amorphous clays, followed by more crystalline zeolites. The process of glass dissolution is then hindered and the dissolution rate reaches the steady value.

In continental and oceanic environments the glass dissolution rates are generally less than 50 μm/1000a and the rate appears to diminish with time. This decrease may be related to a diffusion mechanism involving key chemical species and controlled by the mineralogy of the palagonite layer. Furthermore, corrosion in seawater was much slower than in distilled water [3]

However, not all processes could be addressed satisfactorily using analogues: e.g. radiolysis, thermal fracturing, interaction with metals, cement and other engineered barriers [3] etc.

IV. Applicability of natural analogue information to the CZ vitrified waste

The information, provided by the reprocessing company Mayak about HLW properties of vitrified HLW sums up namely to composition (Al-Na phosphate glass), radionuclide content (Sr, Cs, Y, Ba, Pu, Am, Cm etc.) and declared leachability rate equal **10^{-6} g/cm^2/day** (= **10^{-2} g/m^2/day).** Comparing this value with data gathered in [3], presented in Table 2, it is clear that it seems that the such a value represent an initial glass leaching rate as explained in [4], comparable with short term laboratory experiments (Table 2). It is presumed that glass dissolution rate would slow down to steady state value due to palagonite layer formation with several order value lower values, as explained above, and the values might then decreased toward a natural glass dissolution rates - see in Table 2. However, such an approximation for CZ vitrified HLW should be supported by more extensive research, comprising long term stability test of at least analogues of Al-Na phosphate glasses under simulated repository conditions.

Table.2 Comparison of glass dissolution rates from the laboratory and natural glasses [3]

Form of data	Dissolution rate (g m^{-2} d^{-1})	Reference	Comments
Short-term lab	$1x10^{-3}$	JNC (2000)	H12 reference value
Short-term lab	$1x10^{-3}$	Nagra (1994)	K-1 reference value
Short-term lab	$1x10^{-1}$	Nagra (1994)	K-1 model sensitivity value
Short-term lab	$1.5x10^{-2}$	Nagra (2002)	BNFL glass
Short-term lab	$2x10^{-3}$	Nagra (2002)	Cogema glass
Short-term lab (initial rates)	0.75	Crovisier et al. (2003)	Synthetic basaltic glass leached in the lab in low-silica solution (quasi-analogue)
Short-term lab (initial rates)	0.75	Crovisier et al. (2003)	SON68 'nuclear' glass leached in low-silica solution
Short-term lab (initial rates)	$3.5x10^{-3}$	Techer (1999)	Synthetic basaltic glass leached in high-silica solution
Short-term lab (initial rates)	$3.5x10^{-3}$	Techer (1999)	SON68 'nuclear' glass leached in high-silica solution
Natural analogue	$1.0x10^{-8}$ – $1.5x10^{-5}$	Techer (1999)	Basaltic glass in contact with clays
Natural analogue	$1.5x10^{-7}$ – $1.5x10^{-6}$	Grambow et al. (1985)	Lowest rates calculated from 'isolated' basaltic glass tektites in marine sediments

V. Conclusions

Natural basaltic glasses showed efficient durability to hold trace elements under different conditions and environments. The knowledge gained from basaltic glass studies carried out so far can thus be used in a qualitative form to add general support for the use of glass waste forms as suitable material for HLW.

However, we can only approximate the long term glass leachability values for Al-Na phosphate reprocessed glass, using a comparison of values from short term laboratory experiments and natural analogues. Thorough research on this topic is recommended.

ACKNOWLEDGEMENTS

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Natural Uranium Distribution at KURT site

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I. Introduction

Uranium is a major element among naturally occuring radioactive materials in rocks due to its abundance in subsurface environments, and high uranium contents are mainly found in granite, phosphate, and organic-rich black shales, because these rocks contain the primary uranium-bearing minerals such as uranite, pitchblende, and coffinite [1].

The distribution of uranium and understanding of its migration and retardation processes are also very important in terms of geological disposal of radioactive wastes as radionuclides released from radioactive waste repository might be migrated and retarded in subsurface envir

onments. Thus, the ubiquitous presence of uranium in rocks and groundwaters makes it an ideal natural analogue for studying the behavior of radionuclides in a deep geological repository for the final disposal of high-level radioactive waste [2].

The main objectives of this study are to determine the environmental distribution of natural uranium in groundwater and its geological relationship, and to estimate the uranium species and their mobility under granitic groundwater condition at KURT (KAERI Underground Research Tunnel) within KAERI (Korea Atomic Energy Research Institute) research area in Dajeon, Korea.

II. Materials and methods

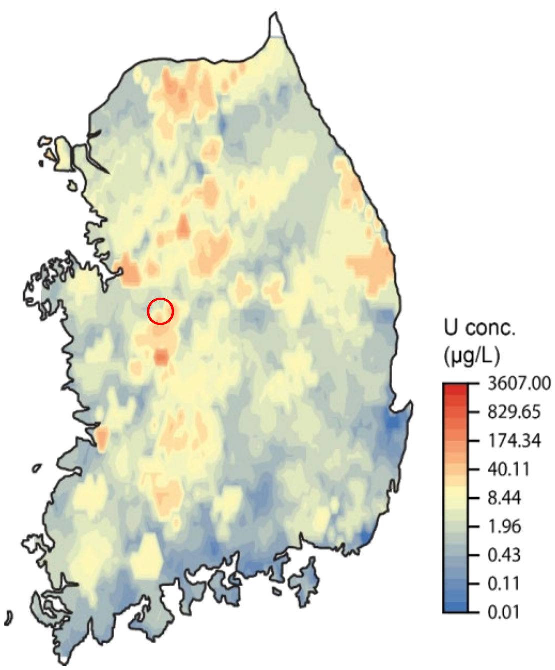

Figure 1: Distribution of geogenic uranium in bedrock groundwaters (N=3009), South Korea. The KAERI research site is located in the red circle area.

A. Geogenic uranium in Korean groundwater

South Korea is a southern portion of Korean Peninsula located in the middle of Northeast Asia. Although the bedrock geology of Korea is quite complicated, it was simplified to five lithological units plutonic, metamorphic, sedimentary, volcanic, and alluvium. Briefly, approximately >70% of bedrocks in the country are plutonic and metamorphic rocks. High uranium concentrations exceeding the WHO guideline level of 30 $\mu g\ L^{-1}$ were found in 160 out of 4140 groundwater wells, predominantly located in the plutonic bedrock region through investigation across the nation ([3], figure 1).

B. KURT

KAERI has studied a geological disposal of high-level radioactive waste (HLW) in Korea. In order to support these studies, KAERI operates the KURT which was constructed in November 2006 to evaluate the safety and feasibility of a geological disposal system under repository conditions. KURT in Phase I had a total length of 255 m with a 180 m long access tunnel and two research modules with a total length of 75 m, and was extended horizontally in 2014 to to secure additional research modules (Phase II in figure 2). For the site characterization of the KURT, a number of researches for identifying the geological, hydrogeological, and geochemical characteristics were implemented in and around the KURT facility. The detail site investigations have also been carried out in 15 boreholes with a depth of 100 to 500 m and one 1,000 m deep borehole. The plutonic rocks are majored around the KURT site, and are largely divided into Mesozoic schistose and biotite granites. Through the fracture orientation analysis and its statistical analysis with a geophysical survey the low-angle fracture was classified as a major fracture group of the surrounding area of KURT and ten fracture zones were finally determined, respctively. These fracture flows were verified by the geochemical distribution of constituents and relative redox environments in groundwaters collected using a multi-packer system.

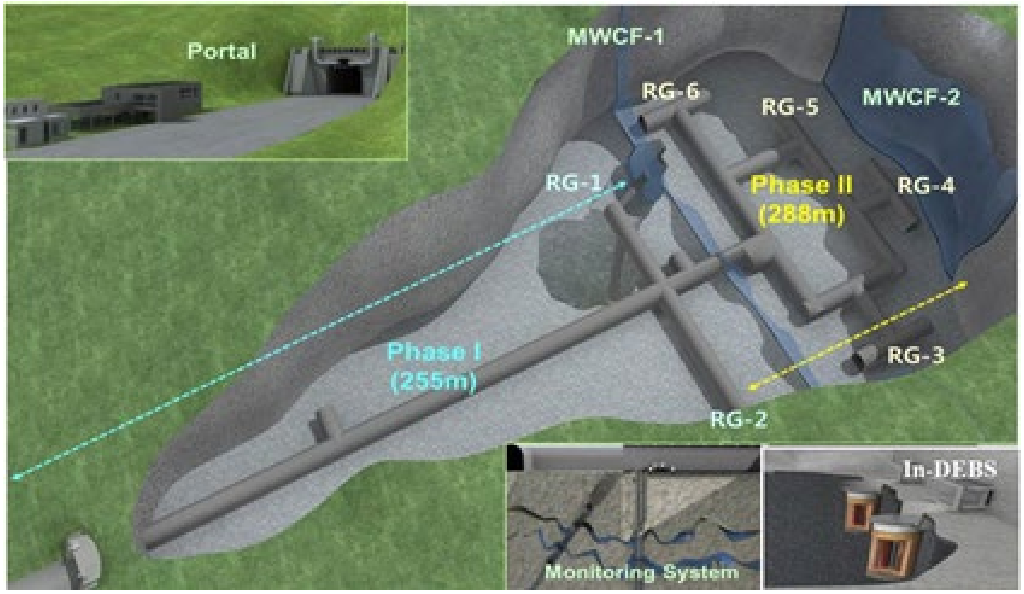

Figure 2: Layout of the KAERI Underground Research Tunnel (KURT). The access tunnel and research modules are all horseshoe shapes, and their size is 6 m x 6 m. The construction and extension of the tunnel were completed by 2006 and 2014 for phase I and phase II, respectively.

III. Results

A. Groundwater chemistry

The results of a geochemical analysis and on-situ measurements of the groundwater samples from the three boreholes in and out of KURT at various depths are summarized in figure 3. The groundwaters around the KURT were characterized by a low total dissolved solid (TDS; <200 mg L^{-1}) and the evolution with a depth from Ca-HCO_3 type to Na-HCO_3 type resulting from excessive water-rock interaction. The fluoride concentration in the collected groundwater samples showed a wide variation of 0.13 to 12.7 mg L^{-1} and an increase with the sampling depth. High-fluoride groundwater in Korea is generally related to the Na-HCO_3 type and occurred in a bedrock aquifer within the area of metamorphic rock and granites. They explained that the origin of fluoride in deep granitic groundwater was mainly from the dissolution of fluorine-bearing minerals such as mica.

The higher uranium concentration (several mg L^{-1}) was detected at a certain depth of deep boreholes even though the sampling dethps were not shallow, and it indicated that alkaline and oxic conditions help increase the mobility of uranium in groundwater. Redox condition, water-rock interaction, pH value etc. were the important factors that influence precipitation and accumulation of uranium in fracture filling minerals at the KURT site. The relations between geochemical factors were evaluated using a geochemical model. In addition, uranium isotopic ratios were used to identify depth or location in which groundwater and solid phases are in secular equilibrium.

B. Groundwater chemistry

In the physico-chemical point of view, the groundwater flow is dominant along the water conductive feature at fractured rock, and this groundwater flow around repository may act on “sender“ of radioactive nuclide from repository to biosphere. Several main water conductive features (MWCF) had been expected in front of KURT Phase I prior to KURT extension (figure 2), and hydrogeochemcial properties in groundwater flow system within monitored boreholes have been monitored during KURT extension (Phase II). At the end of the KURT extension the MWCF2 targeting borehole drilling and pumping was performed, and hydraulic pressures at the specific depth intervals in the three monitored boreholes around KURT were decreased just at the moment. These specific intervals are interconnected with the MWCF2, and are coincident with the regions showing high uranium peaks. This indicates the MWCF2 in the KURT site mainly play role of flow path of uranium.

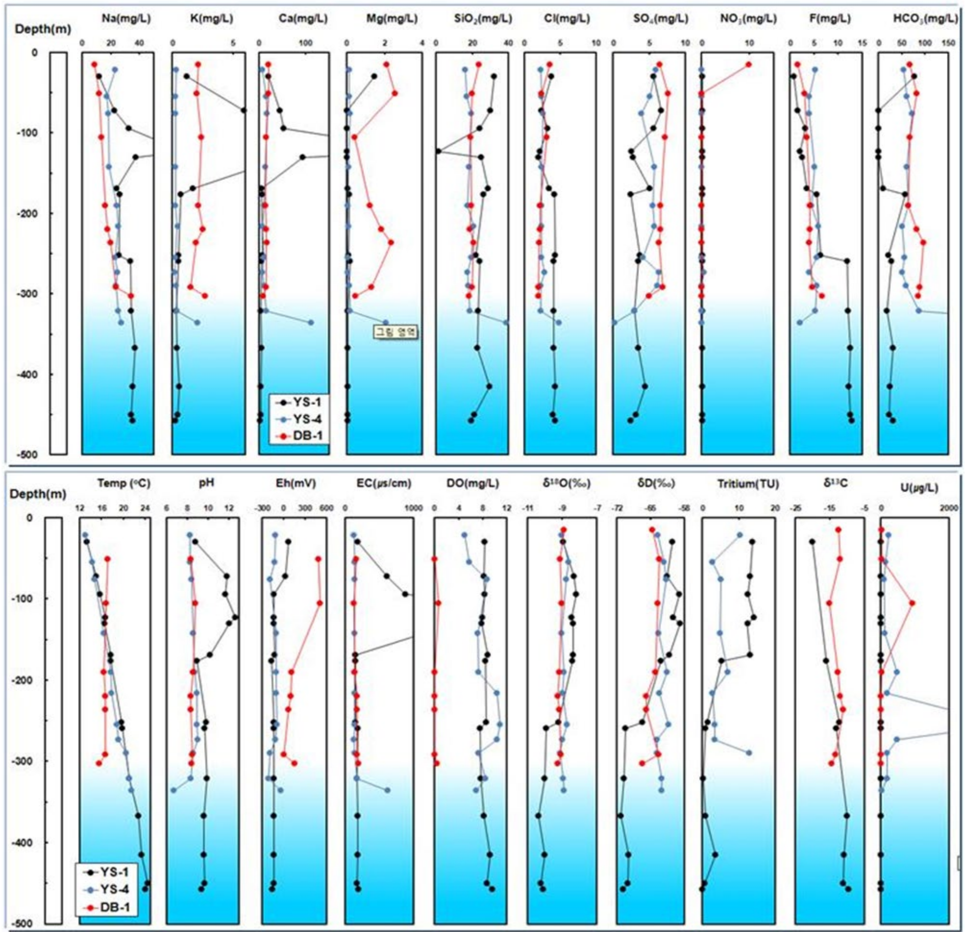

Figure 3: Distribution of major components and geochemical parameters of groudwaters from the KAERI boreholes with a depth.

C. Uranium speciation

The concentration and dominant species of uranium in granitic groundwater sampled from a borehole in KURT were determined using time-resolved laser fluorescence spectroscopy (TRLFS). From the TRLFS measurement in the KURT groundwaters (Figure 4), it was found that uranium mainly exists as $Ca_2UO_2(CO_3)_3(aq)$ in groundwater samples [4]. This result was also supported by speciation calculation using the Geochemist's Workbench (GWB) program [5] based on the OECD/NEA thermochemical database [6], accounting for the formation constants of Ca-UO_2-CO_3 complexes (Figure 5).

IV. SUMMARY

In this study, the distribution and potential migration of natural uranium as well as uranium species were evaluated to investigate geochemical behavior of uranium in fractured granitic bedrock.

- In Korea, the groundwater wells containing high natural uranium located predominantly in the plutonic bedrock region.
- KAERI groundwater samples from specific regions in the boreholes monitored showed an anomaly in U concentraion, ranged of several mg/L in units.
- Water conductive feature as a migration pathway of uranium were traced during the KURT extention.
- From TRLFS measurement and model calculation, uranium mainly exists as $Ca_2UO_2(CO_3)_3$(aq) ternary complex in the KURT groundwater.
- Natural uranium can be used as an analogue for the geochemical behavior of radionuclides in HLW disposal environments, which is very important in the safety case for the deep geological disposal of HLW.

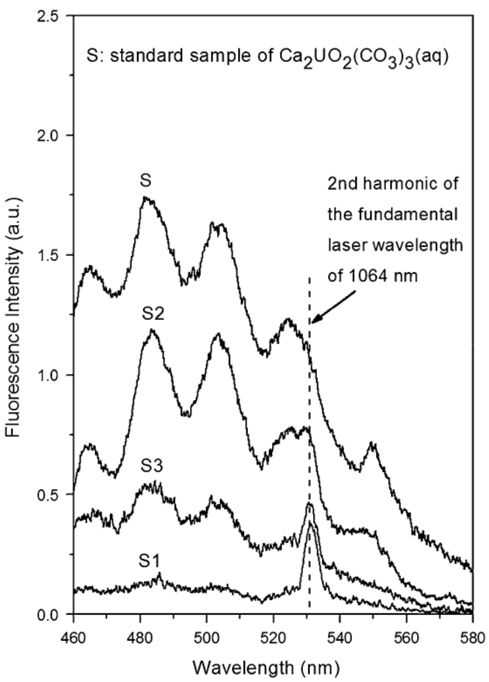

Figure 4: TRLFS results of the groundwater samples compared with a reference standard sample of $Ca_2UO_2(CO3)_3$(aq) synthesized [4].

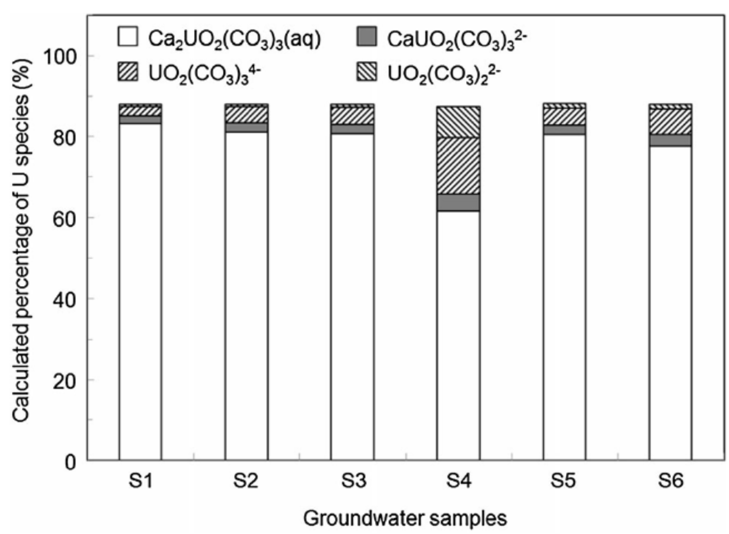

Figure 5: Distribution of major uranium species in the KURT groundwater samples calculated using the GWB program [4].

ACKNOWLEDGEMENTS

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Use of NA in communications: 2 EU-research project Carbon-14 Source Term

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…

I. Introdcution

Carbon-14 is a radionuclide present in some wastes destined for geological disposal that can be released in a gaseous form during waste degradation. If migration of carbon 14 bearing gas from a disposal facility to the biosphere were subsequently to occur, waste-derived carbon 14 is therefore one of the radionuclides that can reach the biosphere first. Only weak betas are emitted during carbon 14 decay, and therefore it is a so-called 'Difficult To Measure' radionuclide. Its measurement in radioactive wastes cannot be determined non-invasively by gamma spectrometry.

The EU Research project CArbon-14 Source Terms (CAST) aims to develop further the understanding of the potential release of carbon-14 from radioactive waste materials under conditions relevant to waste packaging and disposal to underground geological disposal facilities. The project focusses on the release of carbon-14 as dissolved and gaseous species from irradiated metals (steels, Zircaloys), irradiated graphite and spent ion exchange resins [1].

II. Dissemination for different groups

In the management of radioactive waste, several groups of individuals can be identified. It is essential to consider the knowledge and interest of stakeholders (which could be one person, or a group of people, with a specification of their interest, connection, etc.) when planning for the implementation of research results to be incorporated in safety case studies related to a geological disposal facility. Workshops are organised for regulators, waste generators, waste producers and waste management organisations since these stakeholders have at least one responsibility in the management of radioactive waste [2] for example decision to grant a licence for disposal of waste, pay for the costs for disposal, quality control of the processed waste product and defining waste acceptance criteria. Training courses are made for early stage career researchers.

For groups whose interests cannot be specified, mass media communication tools can be used to disseminate the findings of CAST [2]. These tools are newsletters, scientific articles and a website: www.projectcast.eu. At the homepage, a description of natural carbon-14 is given, in order to familiarise the visitor with carbon-14. The CAST interactive website contains components aimed at encouraging visitors to participate. Figure 1 shows an example available on the CAST website: the production and incorporation of natural carbon-14 is visualised when the cursor is held over the main photo.

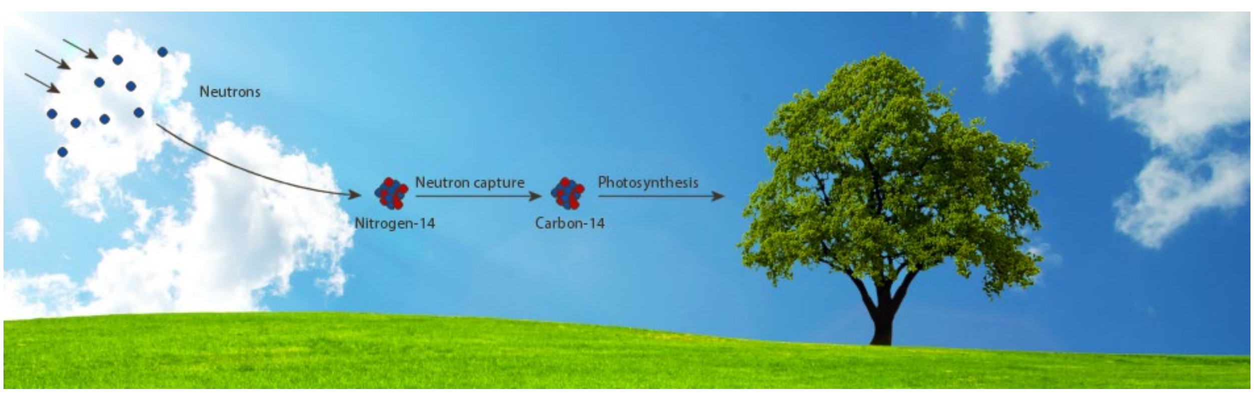

Figure 1: . Visualisation of natural carbon-14

III. Newsletters

For the public, newsletters are written to disseminate the knowledge developed in CAST. Each newsletter focuses on a specific topic using A3 size infographics to illustrate the information. Five newsletters are intended to be produced. The topics are based on the scheduled publications in the Work Packages on Steels (WP2), Zircaloy (WP3), Ion exchange resins (WP4), Graphite (WP5) and Relevance of results in national contexts and safety assessments (WP6):

1) Origin of carbon-14 waste;
2) Radiological characterisation of waste;
3) Experimental approach to determination of release of carbon-14;
4) Analysis and chemical forms of carbon-14;
5) Quantification of source term for safety assessment.

Each Newsletter is intended to contain an example of an analogue associated with carbon-14, in order to familiarise the reader with these topics. An analogue is understood here as a description of the same processes taking place in natural systems and in pure or partly artificial systems such as geological disposal of radioactive waste with engineered and natural barriers. The only differences between both systems are the potential different values in parameters to calculate the processes. In this abstract, the information used to connect carbon-14 in natural systems to carbon-14 in pure artificial systems, in this case nuclear power plants, is described.

IV. Origin of carbon-14

Carbon-14 can be generated by neutron activation of carbon-13, oxygen-17 and nitrogen-14. In the first Newsletter [3], the cosmogenic origin of natural carbon-14 is introduced i.e. the presence of neutrons and nitrogen in our atmosphere. Already in 1970's, only nitrogen-14 was assumed as a contributor to cosmogenic carbon-14 [4]. This origin is not different from carbon-14 in waste, i.e. it is a (mainly) neutron-activated radionuclide formed due to the presence of nitrogen impurities contained in materials used in nuclear power plants and interaction with neutrons available [5].

V. Radiological characterisation

Measurements are difficult for the radiological characterisation of carbon 14 in waste. Frequently, calculations are used to determine the distribution of the carbon 14 content in waste materials. The neutron irradiation history, neutron to carbon 14 reaction cross sections and the concentration of neutron activation precursors are necessary for this determination. The same parameters are necessary to determine the generation of carbon 14 in natural and artificial systems.

The origin of neutrons in natural and artificial systems is different. Neutrons are generated by fission of actinides in a nuclear power plant. Outside the Earth's atmosphere, high energetic particles, e.g. protons, are generated. A cascade of secondary cosmic rays is made by collisions with these high energetic protons (primary cosmic rays). The Earth's magnetic field and atmosphere provide protection against cosmic radiation. A part of these secondary rays are neutrons [6].

In the second Newsletter [7], it is explained why nitrogen 14 is responsible for the main contribution to the generation of natural as well as artificial carbon 14, rather than the other precursors of carbon-14 i.e. oxygen 17 and carbon 13. The natural abundances of the three precursors are 99.636% for nitrogen 14, 0.038% for oxygen 17 and 1.07% for carbon-13. Figure 2 shows the neutron activation cross sections of the three precursors of carbon-14 as a function of the neutron energy. The graphs show the cross sections from the library Joint Evaluated Fission and Fusion File from 2014, in which the latest results were evaluated. The data available in the free on-line libraries from Nuclear Energy Agency (a specialised agency within the Organisation for Economic Co-operation and Development) have been used to compile the graphs for the three precursors of carbon 14.

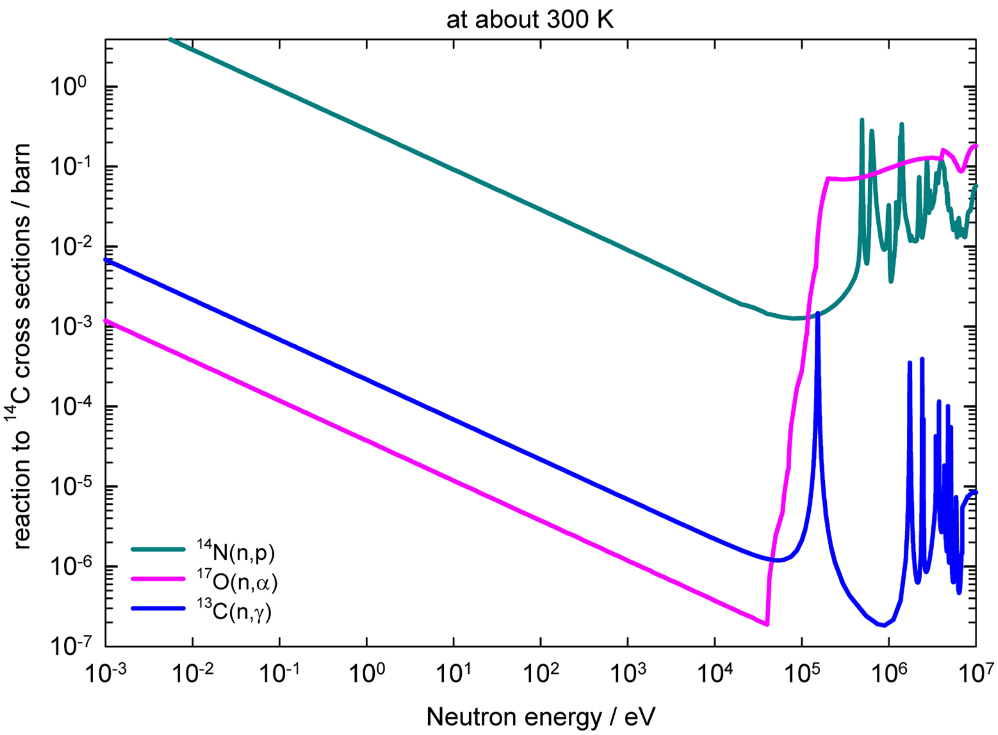

Figure 2: Neutron reaction to carbon-14 cross sections

The energy of neutrons that are generated by fission of actinides is about 1 MeV. The energy of neutrons resulting from collisions with high energetic protons can be several orders in magnitude larger i.e. GeV. The high energetic neutrons lose their energy by collisions with other atoms. Hydrogen atoms are most effective in reducing the energy of neutrons. The operation of a nuclear power plant is focussed of achieving a large thermal neutron flux, as the cross sections for fission of fissionable isotopes such as uranium-235 are largest for thermal neutrons. Water has a high concentration of hydrogen atoms and has therefore a large reducing power. Thermalized neutrons have an energy of about 0.0253 eV at room temperature. Water is therefore frequently used as a moderator in nuclear power plants. The effect of thermalizing neutrons by water is also observed in nature, for example, just a few centimetres below the interface between air and freshwater or seawater, a slight increase of the environmental thermal neutron flux can be measured [8].

The longest-lived lifetime of a neutron in a nuclear power plant is associated with a thermalized neutron. The cross sections for thermal neutrons are therefore used to estimate the carbon 14 content in waste. The reaction relationships relevant to carbon 14 cross sections and the natural abundances of these precursors require the chemical contents of carbon and oxygen to be five and seven orders in magnitude larger than nitrogen in order to contribute to the same carbon-14 content.

About 80% of the Earth's atmosphere is composed of nitrogen. It is easy to understand why only nitrogen is considered as a contributor to carbon 14 from the natural abundances and cross sections of the precursors. During photosynthesis, 14CO2 is incorporated in organic material, forming its carbon skeleton. In living matter, the carbon 14 content can be about 0.25 Bq per gram [9]. In the latest Council Directive 2013/59/EURATOM, laying basic safety standards for protection against the dangers arising from exposure to ionising radiation, the activity concentration for clearance have been set to 1 Bq per gram solid matter for carbon-14 [10]. Based on the carbon 14 content, the amount of material that can be characterised as radioactive waste depends on the nitrogen impurities, thermal neutron flux and irradiation period.
Neutron irradiated steel and neutron irradiated graphite are types of waste frequently resulting from the dismantling of nuclear power plants. The nitrogen content of these waste materials is frequently unknown. For steel, combustion equipment has been used in CAST to determine the nitrogen content for the radiological characterisation of the investigated samples [11,12]. In a nuclear power plant, stainless steel is frequently used for its corrosion resistance,

with carbon steel being used where necessary for its mechanical strength. For example, stainless steel is used for the inner part of the reactor vessel and the outer part is made with carbon steel. Steel scatters neutrons. Consequently, neutron activation takes only place just below the interface of steel and water [13]. It is therefore expected that stainless steel used in a nuclear power plant will only contain carbon 14 generated in the plant. The nitrogen impurities in commercial stainless steel can be 0.10 wt% [14]. Grinding off the surface of stainless steel pieces [15] is therefore a method to reduce the amount of radioactive waste.

Assuming a chemical content of 15 ppm nitrogen in graphite will result in a contribution to carbon 14 by nitrogen of 60%. The contribution to carbon 14 by neutron activation of carbon 13 is then 40%. Frequently, a larger nitrogen content is assumed, for example 40 ppm and 70 ppm in the Romanian and Lithuanian calculations that have been undertaken as part of the CAST project work on irradiated graphite [16]. The contribution by neutron activation of carbon 13 then becomes not a significant issue.

Shielding determines the distribution in magnitude of neutron flux, both for the environmental (natural) system as well as the artificial system of a nuclear reactor. The neutron flux that occurs in nature at altitudes typical for intercontinental flights, related to cosmic radiation, is about 10 neutrons cm 2s 1 [17], whereas, as a consequence of shielding by the Earth's atmosphere, neutron flux at the Earth's surface is consequently smaller, i.e. about 10 3 neutrons cm 2s 1 [8]. The neutron flux in a nuclear power plant reactor is several orders in magnitude larger, for example 1014 neutrons cm 2s 1 [18]. This difference in orders of magnitude in thermal neutron flux causes carbon 14 to be present in waste at hazardous concentrations, even though nitrogen may only be present at impurity levels in materials used in such a reactor.

The nitrogen concentration in materials appears frequently to be unknown, especially before it was decided to use such materials in nuclear power plants. Understanding of the generation of carbon 14 in a nuclear power plant may prevent the potential for hazardous carbon 14 concentrations to be insufficiently considered during dismantling and subsequent waste disposal operations related to nuclear power plant decommissioning, noting carbon 14 activity is not detected by inventory assay techniques such as gamma spectrometry.

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Potential for fractured higher strength rocks to uptake radionuclides from groundwater – a natural analogue study

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I. Introduction

Fractured higher strength rocks (HSR) comprise one of the groups of rock types that may provide a suitable, low permeability host for a Geological Disposal Facility (GDF) for radioactive wastes. HSR encompass fractured igneous and metamorphic rocks, and indurated sedimentary rocks. An important component of the safety case of a GDF hosted in HSR may be retardation of radionuclides within the HSR as they are transported in water out of the engineered barrier system (EBS). For the rock matrix to contribute to retarding radionuclide movement, it must be possible for the radionuclides to move into the rock mass along and away from fractures or other permeable zones through which radionuclide-bearing water is introduced. Movement may be by a combination of advection and diffusion, with a variety of diffusion pathways possible. There must also be mechanisms by which the radionuclides can be retarded by incorporation into the rock mass. These include adsorption to existing grain surfaces, diffusion into grain interiors and incorporation into new, secondary minerals. Radionuclide uptake and retardation mechanisms have been the subject of many experimental studies, both in-situ and in off-site laboratories at the bench scale. Inevitably however, experiments address timescales that are several orders of magnitude shorter than the anticipated duration over which transport and retardation processes are expected to be effective, and are over correspondingly short length scales. As a result they may not give an overview of all the important processes which must operate for significant radionuclide uptake to occur. To complement the experimental studies, RWM is undertaking a natural analogue study of transport and retardation of both radionuclides, and chemical analogues for radionuclides, within higher strength rocks. The overall aim is to develop an improved conceptual model for radionuclide transport and uptake over timescales comparable with those considered by safety assessments. The project commenced in September 2016 and will continue until the end of March 2018. Here, we present interim results of the study, as available in May 2017.

II. Sample Selection

Samples were selected to:

- cover a range of different higher strength rock types, with a range of grain sizes;
- be sufficiently large to enable various kinds of analyses to be undertaken;
- contain fracturing with different characteristics, in terms of complexity, geometries, associated mineral infills and wallrock alteration;

- contain fractures that conduct groundwater with pressure-temperature-chemical characteristics comparable with those likely to occur in the host rocks of a GDF; and
- have corresponding chemical data for groundwaters presently flowing in fractures.

The resulting sample suite consists of:

- two samples of fine-grained meta-tuffs from the Borrowdale Volcanic Group (BVG) of northwest England:
  - one containing a complex vein associated with a zone of fracturing about 30 mm across, again with very little no wall-rock alteration; and
  - a second containing a hairline open fracture, partially-sealed with a very thin film of paragenetically late calcite, but with a network of fine anastomosing calcite mineralised microfractures in the adjacent wallrock, extending for about 5 mm (as identified by X-ray radiography), again with very little wallrock alteration;
- A sample of medium grained Carnmenellis Granite from Cornwall, southwest England, containing a planar fracture with a thin coating of laumontite and calcite on its surface; and
- Two samples of Toki Granite from central Japan:
  - MIU-3/8, a sample of medium grained granite with moderate alteration and a single major fracture in the sample bordered by a narrow zone of fracturing, c. 5mm thick; and
  - MIU3/10 a sample of medium grained granite that is much more intensely altered with a more complex, broader zone of fracturing. The main fracture and associated fracturing are c. 20 mm thick and shows a high degree of alteration.

III. ANALYTICAL TECHNIQUES

The study employs a wide range of analytical techniques, including some techniques that have not been applied previously to studies of radionuclide behavior in potential host rocks. So far, the following techniques have been employed:

- Optical and SEM petrography;
- X-ray radiography
- Digital autoradiography
- Etch track radiography
- ICP-OES and ICP-MS
- Powder XRD
- Glancing incidence XRD
- Synchrotron microfocus XRF and XANES

IV. RESULTS AND DISCUSSION

The suite of samples can be viewed as end-members. At one end of the spectrum, the Carnmenellis Granite and BVG samples provide an opportunity to study mass transport / solute uptake mechanisms in less highly altered rock. At the other end of the spectrum the Toki Granite samples record mass transport / solute uptake mechanisms in highly altered rock. The results to date provide evidence for mobilization and fixation of radionuclides being related to the nature and intensity of alteration of the rock and to the intensity and connectivity of fracturing. In the BVG samples and the Carnmenellis Granite, which show little alteration adjacent to fractures, there has been very little mobilization and fixation of radionuclides, although autoradiography of the BVG samples shows some enhanced radioactivity associated with hematized chlorite in the wallrocks (Figure 1).

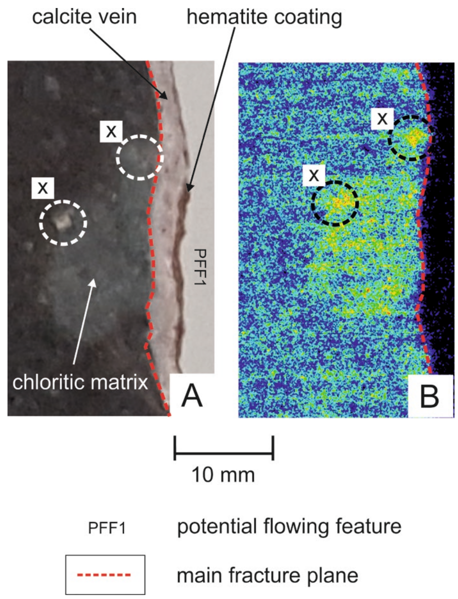

Figure 1. [A] Detail of the upper part of the cut surface of core sample BVG sample SSK70953, with the corresponding autoradiograph image [B]. This shows enhanced radioactivity associated with hematitisation of chlorite in the wallrock matrix adjacent to a fracture.

In the Toki Granite samples, which show considerable wallrock alteration around fractures, there is substantial evidence for the mass transfer of natural radionuclides (Figure 2), with loss of U and Th from the altered zones.

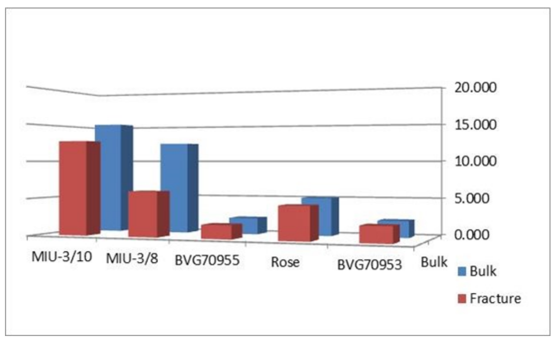

Figure 2. Comparison between U concentrations in bulk rock and wallrocks of fractures in each of the studies samples..The Toki Granite samples, MIU-3/8 and MIU-3/10 clearly show depletion of U in the altered wallrocks compared to the bulk rock.

In the case of the most intensely altered Toki Granite sample (MIU-3/10) there is also evidence that the α-radioactivity is enhanced in the altered wallrocks of the studied fractures, despite whole-rock chemical analyses showing that U and Th have been depleted. The implication of this is that the altered wallrocks have taken up another α-emitting nuclide, which is inferred to be Ra-226. If this is the case, then given the short half-life of Ra-226 (~1600 years) this radionuclide uptake must be occurring within the present groundwater regime. Much of the secondary concentration of radioactivity is closely associated with extensive possible smectitic and chloritic alteration within highly microfractured wallrock. This uptake has possibly occurred at the same time as the U and Th loss. XANES studies at the Diamond Synchrotron in Oxfordshire, UK revealed that U loss adjacent to these fractures is associated with U oxidation in primary U-Th-rich minerals (principally, uranothorianite, bastnaesite and allanite) and their subsequent leaching and migration away from these primary sources (Figure 3).

V. CONCLUSIONS

The studied mobilization and retardation of radionuclides occurred under natural conditions, unperturbed by anthropogenic phenomena such as mechanical evolution and de/re-saturation. The study therefore complements in-situ and laboratory experiments.

The work so far (by May 2017) has demonstrated a close association between uptake or loss of radionuclides and the development of altered wall rocks. These contain secondary minerals formed by water-rock interaction between wall rocks and fluid infiltrated along fractures. It has also highlighted a number of questions which we are continuing to investigate:

1. How do natural radionuclides / analogues for radionuclides occur in the rock? Are they adsorbed on surfaces or incorporated into specific mineral grains?
2. Have grain boundaries provided pathways for the migration of water and solutes between the larger flowing fractures and the rock matrix? If so, what is the interconnectivity between the grain boundary / microfracture network and the major water-conducting features. How far from the larger flowing features have the grain boundary pathways permitted solute and water transport and can we distinguish between transport by advection and diffusion?
3. Have variations in the spatial distributions of natural radionuclides/analogues for radionuclides in primary minerals influenced the mobility of these natural radionuclides / analogues for radionuclides during alteration?
4. What is the relationship between the spatial variations in concentrations of natural radionuclides / analogues for radionuclides and secondary alteration?
5. What does the spatial distribution of secondary alteration present in the samples indicate about mass transport from / to fractures? Are the compositions and proportions of the new phases constant, and if not, do they vary systematically away from the fracture?

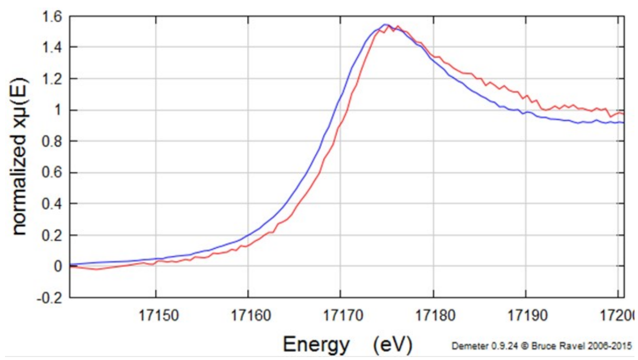

Figure 3: U LIII XANES spectra. Blue curve is from a U-rich microcrystalline phase in MIU-3/8 relatively distal from a fracture. Red curve is from a similar uranium-rich microcrystalline grain in MIU-3/10 in a region of micro-fractures associated with the main highly altered PFF. The two curves are displaced by an energy of 1.5 eV, indicating that the U in the MIU-3/10 grain is significantly more oxidized (edge position difference between U+4 and U+6 is exactly 1.5 eV).

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Use of Natural Analogues in the UK Safety Case

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I. Abstract

It is not possible to simulate in, or extrapolate from laboratory studies, all of the very long-term processes that might affect the safety performance of a Geological Disposal Facility[1] (GDF) for radioactive waste. Furthermore, it is necessary to address processes which are influenced by natural heterogeneities, which include large degrees of uncertainty and which operate over very long timescale. It is therefore necessary to supplement laboratory data with information from in situ underground research laboratory experiments and natural analogues (including archaeological and industrial analogues).

Analogues, whether natural, archaeological or industrial, can demonstrate understanding of aspects of GDF performance and provide evidence that certain materials can persist for long periods of time, or that e.g. processes can be inferred to occur at rates that are slow in comparison with timescales considered in the safety case. Also, the extent to which natural system evolution in the past can be understood and modelled with existing tools and data, gives an indication of the ability to determine the future development of a repository; the use of analogues is integral to a safety case, providing important arguments and building confidence.

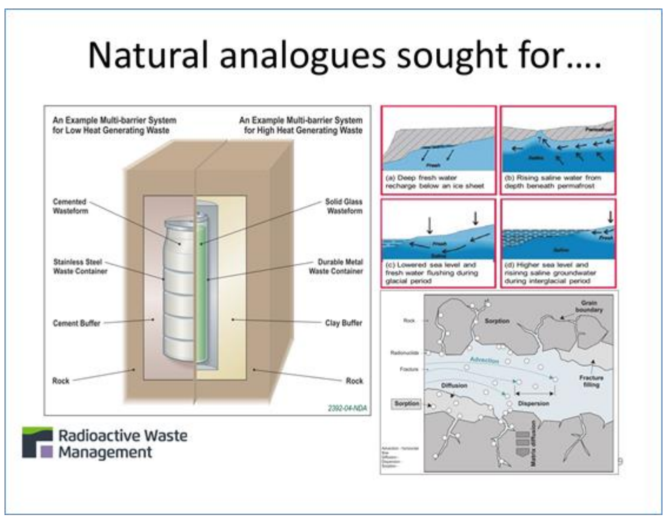

Figure 1 *Illustration from presentation showing the wide range of components relating to a GDF and associated barriers (natural and engineered) for which understanding of and confidence in long-term behaviour can be enhanced by use of knowledge derived from studies of analogues*

GDF analogue topic areas include (see also Figure 1):

1 Engineered Barrier System:
- Wasteform (e.g. natural glasses as analogues of vitrified high level waste)
- Container performance
- Near-field barrier materials (e.g. long term isolation properties of clay)

2 Natural Barrier System
- Long-term evolution of fractured crystalline host rocks (e.g. palaeohydrogeology / palaeoclimate studies)

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[1] A GDF is often referred to as a repository; the terms are intended to be synonymous.

- Long-term evolution of clay host rocks
- Long-term evolution of salt host rocks
- Long-term isolation concepts

3 Radionuclide migration in natural systems

- Retardation in natural systems
- Colloid migration in natural systems

4 Whole system performance

Analogues can provide evidence that certain materials can survive for long periods. However, they do not provide conclusive proof that these materials will survive for the required periods in the environments of a particular GDF, as the conditions under which the analogue material has survived may not match those expected to occur or evolve in the GDF. Therefore, analogues should only be used with caution. Nevertheless, appropriate analogues can be helpful in providing a long-term practical demonstration to support the theoretical and mathematical arguments.

The United Kingdom's Radioactive Waste Management (RWM) produced the 2016 generic Environmental Safety Case (gESC) [1] recently, which explains how the geological disposal of the UK's higher activity radioactive wastes can be accomplished in a way that ensures environmental safety at the time of disposal and in the long term after wastes have been emplaced and the disposal facility has been closed. A key input underpinning the gESC is an approach to safety assessment based on multiple lines of reasoning, involving both qualitative and quantitative analyses. It is noted in the associated ESC Strategy report [2] that:

- *Analogues can be helpful in demonstrating understanding of aspects of GDF performance and provide evidence that certain materials can survive for long periods.*
- *However, they do not provide conclusive proof that these materials will survive for the required periods in the environments of a particular GDF, as the conditions under which the analogue material has survived may not match those expected to occur or evolve in a GDF.*
- *Therefore, analogues will be used with caution, and can only ever provide supporting arguments in an Environmental Safety Case.*
- *Nevertheless, appropriate analogues can be helpful in providing a long-term practical demonstration to support the theoretical and mathematical safety arguments*.

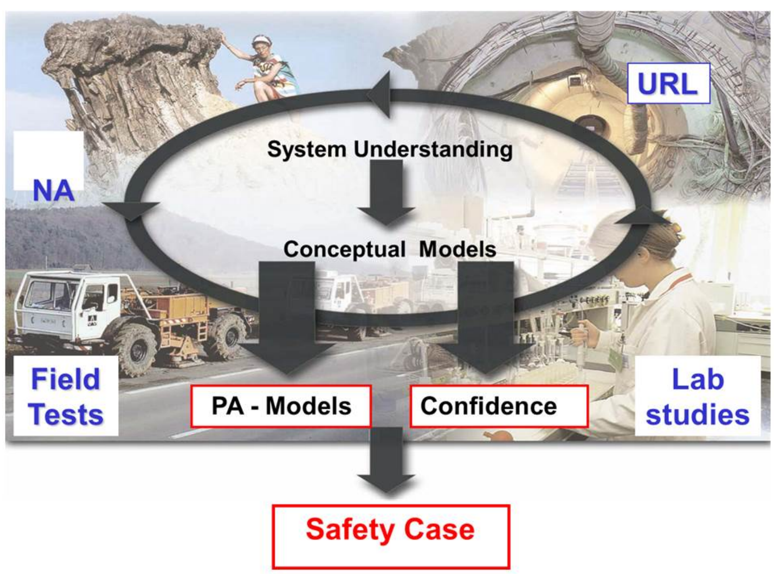

Figure 2 *Illustration showing the interaction between natural analogue studies, field and laboratory experiments, and their input to system understanding and the development of conceptual models (©Bedrock Geosciences)*

Analyses considered in the gESC and the supporting series of research status reports include the use of natural, archaeological or industrial analogues of e.g. material behaviour in a context analogous to an evolving GDF; RWM has published a catalogue of natural analogues for input to its safety case studies [3]. Figure 2 illustrates how components contributing to a safety case can inter-relate.

It is therefore evident that the use of understanding derived from studies of suitable analogues in the context of aspects of the GDF is embedded in the approach to developing the gESC; going forward, it is to be expected that this approach will persist in the RWM programme.

This presentation considers the UK and international knowledge base on analogues potentially relevant to radioactive waste management, and discusses how the level of their involvement in the current RWM gESC may be an artefact of the generic state of the UK GDF site selection programme, and how this is anticipated to evolve as this programme becomes site(s) specific.

The presentation notes the RWM knowledge base contains information on a lot of analogues, see [3], which itself is utilised and referred to frequently in RWM Research Status Reports, e.g. [4]. However, explicit reporting of the use of information derived from the knowledge base on analogue studies is arguably at a lower level in the gESC itself, although this document is fully supportive of the relevance of analogues to a safety case.

Stepping away from specific consideration of the RWM gESC and taking a broader overview of the development of an Environmental Safety Case (ESC) – also frequently referred to internationally as simply a safety case – by a national waste management organisation (WMO) responsible for GDF implementation, it is postulated that the use of analogues is likely to vary along an organisation's road from a generic to a site-specific programme basis, and that a "time lag" in the deployment of a more extensive knowledge base on analogues into a developing ESC could be expected. Possible reasons for this are explored, for example:

- Research activities in respect to enhancing the analogues knowledge base, and activites associated with the authoring of an ESC, may be undertaken by different teams in an organisation (noting this is likely to vary organisation by organisation);
- Are the approach taken to ESC development and the approach taken to enhancement of the knowledge base compatible? (Is there an unintentional side-effect of not appreciating or understanding how thorough and appropriate use could be made of analogues from the knowledge base in ESC development?)
- Is there an implicit preference when developing an ESC to prefer a quantitative approach over a more qualitative one? Does this affect the role that can be afforded to analogues throughout the development of an ESC?
- It there an issue of simply being unsure what to make of analogue information or how it could be used in an ESC, given the associated caveats and uncertainties?
- Is information / additions to the knowledge base as derived from an analogue study actually being presented in a manner that is 'sympathetic' to the modus operandi of the production of an ESC?
- It is unlikely that a WMO starts developing an ESC from a blank piece of paper; often it is the case that 'something' exists beforehand on which to build on 'next time around' – in recognition of this, does an approach to developing an ESC akin to 'it's always done this way' best allow information from analogues to be most appropriately considered?

In consideration of such points, the presentation confirms that a WMO with an ambition to produce an ESC that is as thorough as it can be, in consideration of attaining regulatory requirements, clearly needs and should want to exploit fully analogue information and the related enhancement brought to the knowldge base.

This could suggest the need for an ongoing 'campaign' to keep the profile of analogues, and their essential input to, use in, and benefits for, an ESC high in the WMO mindset.

The presentation concludes that there is clearly an onging key role for the Natural Analogue Working Group to play here, to ensure the 'message' regarding the relevance of analogues to building robustness and confidence in an ESC is maximised, and that analogues and their use in enhancing the knowledge base - from acquired science to deployment as part of an ESC - are fully exploited.

Finally, the presentation confirms that analogues provide:

1. **Significant opportunities in communications and staff training associated with radioactive waste management.**

2. **Increased confidence** in extrapolating results from laboratory and field experiments to the repository environments, with broad deployment – their use is not restricted to limited number of components of a safety case.
3. **A key role in the development of an integrated safety case that draws on all of laboratory experiments, testing in underground laboratories, modelling and natural analogues.**

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Use of natural analogues in the Finnish safety case – status update on Complementary Considerations

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I. INTRODUCTION

Posiva is preparing to update the safety case for the operational license application for a spent nuclear fuel repository at Olkiluoto, Finland; the license application is planned to be submitted to the authorities around the year 2020. This work includes updates for safety case reports published in TURVA-2012 safety case. In the 2012 safety case, natural analogues (NA) were mainly discussed in the Complementary Considerations (CC) report [1], but also e.g. in the Features, Event and Processes report [2], as well as in the Performance Assessment report [3]. This highlights the fact that NA information is linked to many discussions related to process understanding throughout the safety case. An update of the CC report is now being prepared in parallel with other parts of the safety case update, aiming at a better integration with the other safety case reports. Some plans for the contents update are described below, also related to recent NA results that were not available for the previous safety case.

II. REGULATORY CONTEXT

In addition to the international guidelines about the safety case e.g. [4], using NA information is specifically mentioned in the regulatory guides in Finland concerning the long-term safety of nuclear waste disposal [5]:

- first, natural analogues are seen as part of the basis for high-quality scientific expertise ([5], Annex A, A07)
- and second, in cases when a scenario cannot be comprehensively and reasonable assessed by means of quantitative analyses as a means of providing relevant information on more qualitative considerations, natural analogues can be used to assess the scenario outcome ([5], Annex A, A10).

This sets the objective to support process understanding and highlights the role of complementary considerations especially in relation to geological timeframes, since the reliability of modeling and experimental results decrease as the time intervals examined become longer.

III. OBJECTIVES OF COMPLEMENTARY CONSIDERATIONS

The update of CC report takes into account the feedback from the regulator for the previous version of the report [1], changes in Posiva's own requirements and design, as well as any updates on the general national and international regulations or recommendations [6].

For example, the repository for Low and Intermediate Waste (LILW) from the encapsulation facility needs to be fully integrated in the safety case analysis. The LILW repository is planned to be constructed in the vicinity of the deep spent nuclear fuel repository and thus needs to be considered throughout the safety case. This brings in a few new topics regarding the materials used in the LILW and the waste inventory characteristics. The location of the LILW at less than 200 m depth, meaning that the geological environment is somewhat different than at the repository depth ~-450 m.

Regarding the EBS design, a more detailed analysis of the closure structures is needed and CC could provide some complementary information. The general objectives of CC are to:

- describe the hazard presented by the radioactive waste and frame it in the context of other hazards (e.g. natural radiation hazard),
- discuss the selected waste management option,
- provide means of putting safety assessment results in context (complementary safety indicators), and,
- support and assess the safety case conceptual models, process understanding and site suitability, especially in the geological time frame by:
    - presenting evidence and understanding of the past and future evolution that can be gained from observations at the site, including its regional environment, and
    - presenting relevant information from natural and anthropogenic analogues for the repositories (SNF and LILW), their components and the processes that potentially could affect safety; and
    - addressing particularly diverse and less quantifiable types of evidence and arguments to be used to enhance confidence in the outcome of the safety assessment.

Geological evidence, or natural analogues, in broad sense, are linked to all these objectives.

IV. LINK TO THE SAFETY CASE

The planned safety case is a portfolio of main reports supported by background reports (Fig. 1.). The update of the CC report will aim to strengthen the link between Features, Events and Processes (FEPs), performance assessment and other relevant parts of the safety case in a way that the main discussions regarding natural analogues are presented in CC, but the integration with other safety case reports is enhanced. This adds both to consistency and comprehensiveness of the safety case, as well as to transparency and readability of the final safety case. Since FEPs are planned to be presented as a database, the component specific discussions of processes is done in the safety case reports (especially CC, PAFOS and AOR).

SAFETY CASE PORTFOLIO

Synthesis
Description of the overall methodology of analysis, bringing together all the lines of argument for safety, and the statement of confidence and the evaluation of compliance with long-term safety constraints
Design Basis (DB)
Safety functions, performance targets and design requirements, their basis and the links between them
Initial State (IS)
Initial state of the repository system and the present conditions of the surface environment
LILW Repository Assessment (LILW-RA)
Assessment of the long-term performance of the repository for LILW from the encapsulation plant and identification of interactions with the SNF repository
Performance Assessment and Formulation of Scenarios (PAFOS)
Assessment of fulfilment of performance targets taking into account the expected and alternative climate and surface environment evolutions. Scenarios formulation based on uncertainties/deviations identified in the assessment
Models and Data (M&D)
An overview of models and data used in the performance assessment and in the transport, release and dose calculations for the disposal system
Analysis of Releases (AOR)
Overview of the main results from the radionuclide release and transport modelling from the repository system to the surface environment and evaluation of radiological consequences
Complementary Considerations (CC)
Supporting evidence for safety including natural and anthropogenic analogues

Figure 1. The planned safety case portfolio reports. (SNF, spent nuclear fuel; LILW, low and intermediate level waste).

V. SOME SPECIFIC UPDATES

A. Complementary safety indicators

Complementary safety indicators are updated in the CC report and will be used to support the results of the analysis of radionuclide releases report (AOR in Fig. 2). Complementary indicators will be defined for activity releases and concentrations in the repository system (e.g. activity concentration in the bedrock, activity fluxes in groundwater and uptake of ^{14}C by biomass) as well as for doses (e.g. radon in indoor air, see [1]). The aim of the update is to provide a set of indicators that can be used for various scenario types. Parallel work is hence required for also with PAFOS (Fig. 2), where scenarios are defined. Complementary indicators will be set also for LILW-repository specific releases.

B. Evidence and understanding of the past and future evolution of the site

Site suitability is largely discussed in the site description documentation outside of the safety case main reports. However, topics that are considered safety relevant, are included in the CC discussion, also from the regional point of view. These discussions can be related for example to regional considerations regarding groundwater recharge and its geological controls. Specifically, the recently finalized Greenland Analogue Project (GAP) (GAP, see [7]) and the ongoing Posiva's Saimaa project will provide further scientific input to CC. The Saimaa project aims at studying dilute water intrusion processes in the bedrock near the southern Finland end-moraines, representing the condition where the ice sheet remained at the site for extended period of time.

The future evolution of the site is also affected by the land uplift process mostly during the next 10 000 years, the time period that is the main focus of the biosphere assessment. To understand the development of the surface environment during this period, analogue sites have been used for future surface environment successions. The use of these future site analogues will also be more extensively described in the CC update.

C. Natural and anthropogenic analogues for the repositories (SNF and LILW)

Regarding the EBS design, a more detailed design of the closure structures is now needed and the analysis of their performance might benefit from the additional support of NA. The integration of the LILW repository does not introduce new materials, as concrete is also used for the construction of the SNF repository, but the LILW inventory brings some additional processes into consideration, e.g. cellulose degradation.

Furthermore, additional natural analogue research projects have recently been completed in relation to repository materials and they can now be integrated in the CC update. These include e.g. the high-pH bentonite study at Cyprus (CNAP, see [8]) and bentonite deformation investigations done at Kato Moni, Cyprus [9]. These and other new information from the literature will be reviewed considering the Olkiluoto site and relevance to disposal conditions in Finland.

D. Enhancing confidence in the outcome of the performance and safety assessment

In addition to NA, CC will include other contents, for example URL considerations, operational analogues, and some discussion on the geological disposal option in general and hazards related to it. Thus, together with extensive site- and design-specific NA discussion, CC can provide an extended overall picture of the disposal system evolution supporting the performance assessment (PAFOS, Fig. 1).

For the Synthesis report (Fig. 1), a network of safety statements can be formulated and supported by using a number of arguments; the supporting arguments are mapped to design considerations, performance assessment results (PAFOS, Fig. 1) and radionuclide release and transport assessment results (AOR, Fig. 1). Supporting arguments from CC can also be mapped to the safety statement network thereby providing additional lines of evidence.

VI. DISCUSSION AND CONCLUSIONS

NA information form the bulk content of the CC approach in the safety case and the upcoming report will be updated in parallel with other updates in the safety case. The update will be based on the previous report in Posiva's 2012 safety case (see Posiva 2012; Reijonen et al. 2015) for the repository site in Olkiluoto Island in Finland.

In many other safety evaluations worldwide, natural analogues have also been utilised, but more often embedded within other (supporting) reports, i.e. no individual report is dedicated to discussion of specific natural analogue support to the safety case. Both approaches have their advantages, but complementary considerations allows elaboration of the input that NA studies bring to the conceptual models, assessment of long-term behaviour of repository materials, testing of numerical models etc. in much more detail than when including the information in other safety case reports. In addition, presenting similar types of information in one individual report also provides an effective way to spot any gaps in the knowledge base, in effect a form of screening of scientific understanding in relation to long time scales.

VII. ON IMPLEMENTATION FOR OTHER PROGRAMMES

Complementary considerations approach can be implemented at any stage of a disposal project. Despite of the approach taken on how to present NA information, of importance is that when design and site details become more precisely defined as the project evolves, then the supporting natural analogue information must also become more focussed and design and site specific. Relevance of a given natural analogue investigation depends heavily on the repository system to which it is applied: to illustrate this, an overview of natural analogue information in the safety case at various stages of a repository project is presented in Table 1.

Table 1. Using natural analogue information at different stages of the disposal project.

Objectives of CC	Generic stage	Site & repository design selected	Advanced stage
Site considerations	e.g. FEP NA analyses: Ranges of conditions (regional analogues[1])	Screening of FEPs, update FEP-NA analysis. Regional considerations[2] for site evolution to enhance predictability. Self-analogues to examine detailed site properties.	Screening of FEPs, update FEP-NA analysis. Site / scenario specific regional analogues /considerations[1] (e.g. glaciation, tectonic evolution etc.).
Design considerations	e.g. FEP NA analyses: Material performance in generic range of conditions.	Screening of FEPs, update FEP-NA analysis. Examination of the long-term stability of the same materials as will be present in the repository (e.g. bentonite)	Update by process specific analogue information based on the uncertainties/gaps in the overall safety case.
Waste considerations	Description of the waste inventory and mapping the relevant NA information (FEP NA analysis).	Examination of the long-term stability of materials which mimic the waste matrices (e.g. uranium ore for spent fuel) considering site specific conditions.	Transport considerations in site specific geosphere and biosphere.
Stakeholder communications	Basis for geological disposal via examples. Considerations of disposal options. Consideration of repository design options.	Use of clear examples which mimic aspects of the repository design (e.g. the Dunarobba fossil forest encapsulated in clays as an example of the role of bentonite in the EBS). Preferably examples used in the generic stage can be elaborated here.	Explaining the safety concept and support for the robustness of design and suitability of the site. Preferably examples used in the generic stage can be elaborated here. Confidence for the safety assessment results.

[1] Regional analogue, which refers to more direct type of analogue to site.

[2] Regional consideration refers to studying scenario related processes and gaining broader understanding of processes through regional geology. This can be e.g. overall understanding on the deep groundwater evolution and characteristics that affect it.

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International Bentonite Longevity (IBL) project: an introduction

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I. Overview

Kunimine Industries' (KIC) Tsukinuno bentonite mine is a source for Miocene age Na-bentonite (with Ca-bentonite near-surface) and the site holds great potential for studying processes of direct relevance to safety cases (SC) for radioactive waste repositories which will utilise bentonite as part of their multi-barrier safety system (see discussion in [1], for example).

The Tsukinuno mine and its environs are ideal for studying long-term, safety-relevant bentonite processes, including:

- Bentonite erosion – both extreme case (river erosion at the surface) and more repository relevant at depth in the tunnels where water conducting features contact the bentonite
- Saturation state – natural saturation states of bentonite in differing environments (on the surface and at varying depths underground, dry and wet host rock conditions) for comparison with ongoing short-term, laboratory and underground rock laboratory (URL) tests
- Bentonite density changes (swelling and heave) due to exposure to groundwaters/meteoric waters
- Bentonite water interaction processes with fresh and deeper groundwater chemistries – for example, changes in cation exchange capacity (CEC) and exchangeable cation composition (EC)
- Bentonite reaction with mudstone and siltstone host rocks

In the Tsukinuno area, some 21 bentonite layers vary in thickness from a few cm to ca. 7 m, providing information of relevance to the scales of both the buffer and backfill. In addition, bentonite compositions vary, providing the potential for studying processes in relation to various initial states of the buffer/backfill. The bentonite also occurs across a range of depths and tectonic/geomechanical environments (due to their location in anticlinal-synclinal geological environment: Figure 1), so allowing assessment of the impact of varying lithostatic pressures and stress/strain fields on the material.

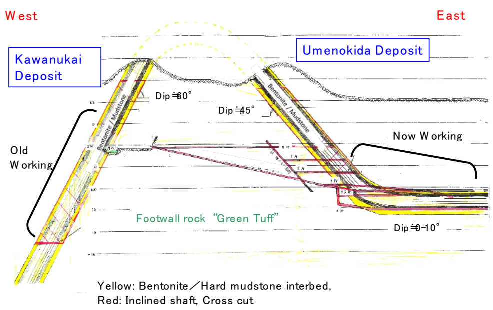

Figure1:cross-section of the Tsukinuno bentonite mine showing the working drifts and main bentonite deposits (courtesy KIC)

Mining has been ongoing at the site for several decades, so providing:

- direct access to surface exposures (Figure 2)
- access via drifts and shafts to bentonite exposures in the working mine (Figure 3a)
- access to existing (and potentially future) drillcores (Figure 3b)

II Processes of interest

Currently, the project is in an initial planning and data mining phase, but it is intended to examine a suite of processes of SC relevance at the site, including:

Figure 2: view of surface exposures of shales and bentonites in the bed of the river immediately NW of the Tsukinuno mine (H.Reijonen, GTK)

Figure 3: a (left) typical bentonite exposure in the mine tunnels B (right) on-going exploration drilling in the vicinity of the mine (courtesy KIC)

A. Bentonite sampling

Recent reviews of drilling methods [e.g. 2, 3] indicate that currently utilised methods induce damage in the samples ranging from artificial fracturing to altering the *in situ* density. Approaches for minimising such damage to bentonite cores are already utilised in the oil industry and it is proposed to adopt these practices here to assess their relevance to future radioactive waste R&D, including sub-sampling laboratory material and drilling cores from full-scale experiments in URLs.

B. Bentonite characterisation

Bentonite samples investigated will be characterised for their physical and chemical properties. In addition to standard chemical and mineralogical investigations to complement existing information [e.g. 4], geotechnical properties (swelling pressure, plastic limit etc.) need to be investigated. It is also suggested that detailed investigations are done regarding the internal structure of the bentonite, so allowing direct comparison with compacted industrial bentonites of the buffer and backfill. These studies should include petrographical investigations (determination of the textures, degree of cementation, accessory mineral variations etc. – cf. [5]).

C. Bentonite erosion – extreme case and swelling behaviour

The stability of bentonite across a range of groundwater salinities is of interest (see [6], for example), but especially in relation to potential dilute water intrusion due to an extended temperate period (i.e. taking global warming into account) or glacial retreat. Chemical erosion of bentonite is related to conditions where there is dilute enough groundwater to produce bentonite colloids and high enough flow to transport them away from the repository. The chemical erosion process has been acknowledged in several recent SC (e.g. from NUMO, Posiva and SKB), but ongoing modelling studies supported by dedicated, short-term laboratory programmes have produced ambiguous results.

This indicates that longer-term ‘experiments’ are required which can assess the likely long-term impact of the chemical erosion of bentonites. To date, little has been done in this area, but exposed bentonite beds in the base of a river in the immediate vicinity of the Tsukinuno bentonite mine (Figure 2) offer an unique site to study potential bentonite erosion at the repository scale (if not in a repository environment). In the river bed setting, it is possible to investigate how the unconfined nature of the bentonite in the river bed has affected the density of the bentonite and how this may have impacted gel/sol formation and subsequent erosion. This should be examined by sampling bentonite directly from the river bed and taking control samples from nearby sites unaffected by the river for comparison.

In the mine tunnels, there is also the possibility to examine bentonite erosion under true repository *in situ* conditions where groundwaters moving in and along the interbedded mudstone and siltstone host rocks react directly with the bentonite layers.

D. Bentonite saturation states (preliminary study)

Bentonites in the repository engineered barrier system (EBS) will be subjected to natural hydrostatic pressures. Saturation processes dictates the type and rate of many geochemical processes taking place in the bentonite and full saturation is assumed in most repository designs as a long-term condition for the bentonite. However, the period before full saturation can be very long when the decay heat of the waste affects near-field conditions, especially in cases where the host rock is relatively dry. By looking at bentonite occurrences at repository relevant depths, some open questions can be answered:

- Are safety case assumptions too conservative?
- Can further studies help in conceptualisation of the bentonite-water processes so that the SC applications would be more realistic?
- Natural bentonites seem to be closed/half closed systems – what implications does this have on the mixing tank type of safety assessment?
- What is the natural saturation state of bentonites and how does it vary as a function of the surrounding local geology?

For repository projects, realistic assessment is not only safety relevant but also allows optimisation of EBS design.

E. Repository depth considerations – specific underground studies

The above noted work should act as both a proof of concept (i.e. that long-term changes in saturation of the bentonite can be defined to an acceptable degree) and as an extreme end-member of bentonite behaviour when the source of water is effectively unlimited. However, for a more repository-relevant assessment of the likely long-term saturation state of bentonite, it is necessary to consider a more relevant environment and this will be done in the mine tunnels. Here, bentonite will be examined under relevant lithostatic stresses and representative groundwater fluxes in the Tsukinuno bentonite mine.

F. Stakeholder communication

As an integral part of the overall project, material [e.g. 7] will be produced which can be utilised for more general, technical and non-technical communication purposes. The main aim is to produce multi-media materials which will clarify the role of bentonite in repository performance to a range of stakeholders.

III. Conclusions

The International Bentonite Longevity (IBL) project is currently in a planning and data mining phase and it is intended to progress to further phases of detailed examination of several processes of direct relevance to repository EBS longevity. These include:

- bentonite erosion: both an extreme case in a local river bed and repository SC relevant systems deep in the mine
- assessment of how swelling behaviour differs in the unconfined systems representative of the repository operational phase and in the confined systems representative of the repository post-closure phase
- bentonite saturation states: by looking at bentonite occurrences at repository relevant depths, some open questions can be addressed. For example, examining saturation states under relevant lithostatic stresses and representative deep groundwater fluxes will enable improved conceptualisation of bentonite-groundwater processes so that SC applications would be more realistic
- stakeholder communication: material will be produced which can be utilised for more general, technical and non-technical communication purposes
- technical development: assessment of approaches for minimising sample damage to bentonite cores to define their relevance to future radioactive waste R&D, including sub-sampling laboratory material and drilling cores from full-scale experiments in URLs

IV. Acknowledgements

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Investigation of postglacial faults in Finland - An update

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I. Introduction

As Finland is situated at high latitudes, future glaciations may pose potential risks for long-term safety of the nuclear waste repository. The slow loading of horizontal stresses during the advance of an ice sheet and rapid unloading of the vertical stresses during the melting stage forces the bedrock to readjust to the changing conditions. The recorded present-day uplift rates in Finland are up to 9–10 mm/a, and the overall uplift has been nearly 1 km since the Weichselian glacial maximum ca. 20 ka ago.

Postglacial faults (PGFs) have been described from Finland, Norway and Sweden since the 1960s (Fig. 1) [e.g. 1, 2]. In 2014 the Geological Survey of Finland and Posiva jointly launched a country-wide LiDAR DEM-based search for PGFs, paleolandslides and other morphological features of Quaternary deposits possibly related to post- and late-glacial seismic activity. The project called PGSDYN (Postglacial faults and their dynamics) has three main goals: 1) to reassess the existence of PGFs and other seismically-induced features in the southern part of the country, 2) to continue investigations around and at the extensions of the known PGF zones in northern Finland, and 3) to improve understanding of the reactivation mechanisms, internal geometry and other properties of the faults.

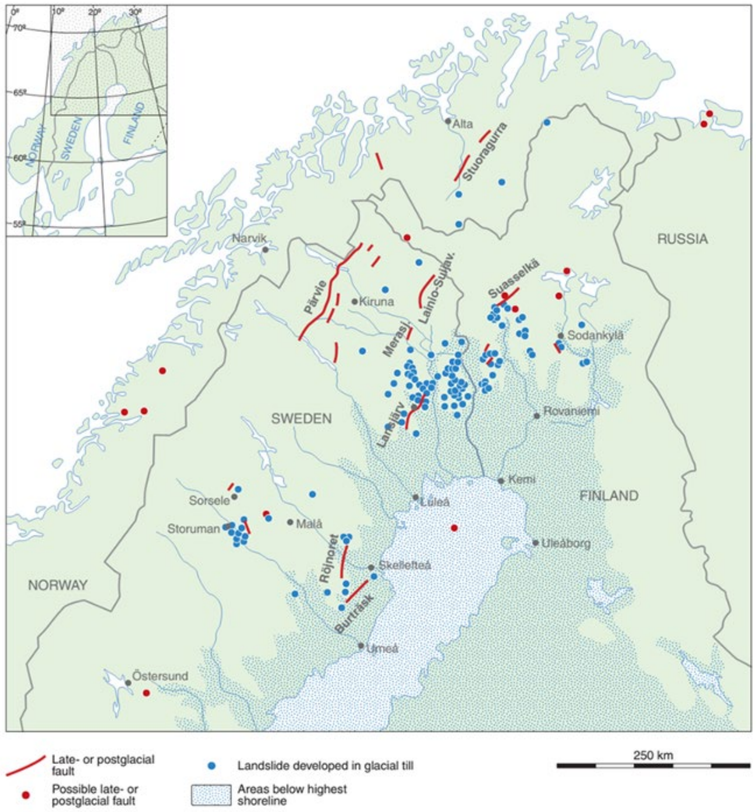

Figure 1. PGFs and landslides identified in northern Scandinavia by the year 2008 [1]. Since that date large number of new landslides and PGFs have been detected from LiDAR maps, most of them in the same regions as the old ones.

II. OUTCOME

By the date of the NAWG workshop in 2017, about 85% LiDAR coverage of the land area of Finland has been reached. Various types of information has been collected and stored into a specific database and the analysis of the data has begun [3,4, 5]. Altogether 10 major PGF's have been observed. They are composed of 126 individual segments (subfaults) underlining the complexity of the tectonics [6]. More than 120 lanslides have been identified, characterized and classified (Fig. 2), and 15 of them have been dated with radiocarbon of the buried organic material [7]. Additionally, 125 potential PGF features identified from LiDAR DEMs have been checked in fieldwork and shown to be either natural (e.g. erosional features, iceberg tracks) or man-made artefacts (Fig. 3).

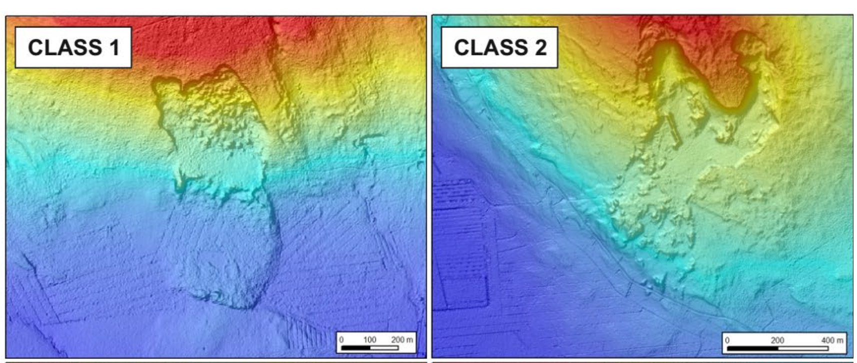

Figure 2. Hillshaded LiDAR DEM showing paleolandslides from Kittilä and Kolari [7]. Based on the mode and appearance, the landslides in Classes 1 and 2 are related to recent (past 10 ka) seismic activity. Basemap and LiDAR © the National Land Survey of Finland.

Figure 3. A) The 80-m-long, 5-m-wide and 4-m-deep trench at Riikonkumpu, northern Finland was excavated through glacial sediments to reach the surface of weathered phyllitic bedrock. B) Vertical sections of the trench were logged and photographed to create imagery of the sedimentological details and the fault-propagation formed during a paleoseismic event [6].

The main conclusions include:

- PGFs are focused on the northern part of the country. Only one fault, the Lauhanvuori PGF, could be confirmed from the central and southern part of the country (Fig. 4). However, suspected seismites (seismic induced deformation in soft sediments) do occur in these areas
- Marine geological soundings provide evidence of potential subsea PGFs and seismically-induced sediment features in the southern sea areas
- The geometry of recognized PGFs is often complex and distinctively segmented along strike making their tectonic analysis challenging (Fig. 5)
- All PGFs studied by drilling and trenching are reactivated faults within ancient deformation zones
- Datings of landslides has provided strong indications that the recurrence cycle for seismic activity is 3000-4000 a
- Moment magnitude estimates based on fault lengths, vertical displacements and area-volume data of landslides all suggest consistently MW $\approx$ 6.7 – 7.7 for northern Finland.

III. Ongoing And Future plans

PGSDYN is scheduled to be completed at the end of 2017. The planned field work will be finalized during the forthcoming summer and the final report will be published in 2018 as Posiva report series. All the data collected will be stored in a database, which will become public via GTK online information services. The database will be continuously updated as new information will emerge through GTK's in house projects or from other sources.

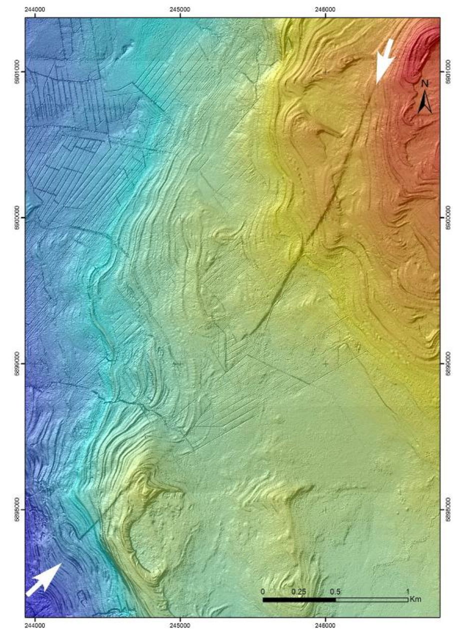

Figure 4. A possible PGF from Lauhavuori (western Finland) discovered during the screening process. The fault scarp indicated with white arrows in LiDAR DEM image cuts through ancient shoreline beach ridges above 120 m a.s.l., which formed prior to about 9500 cal year BP [5]. Basemap and LiDAR © the National Land Survey of Finland.

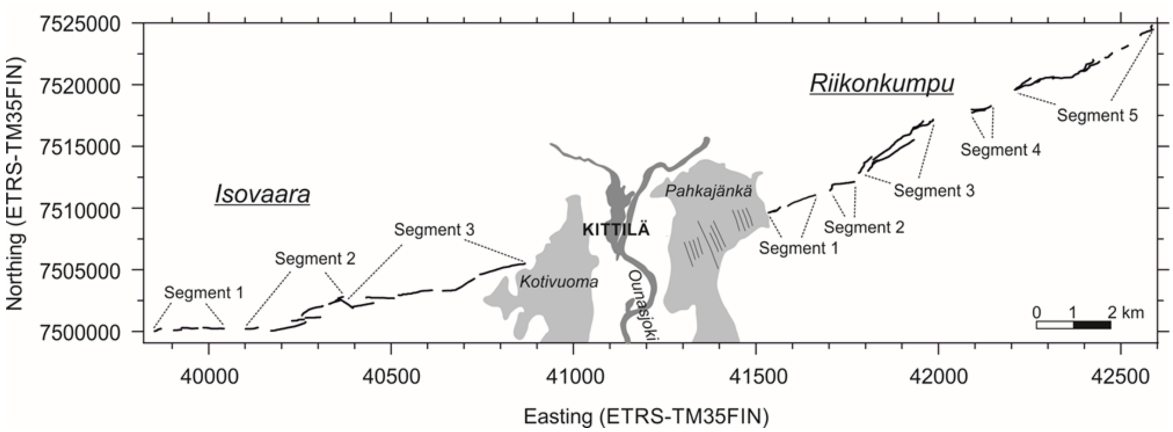

Figure 5. Geometry of the 30-km long Riikonkumpu and Isovaara fault systems [6]. Note that in reality the PGF system is trending roughly NNE.

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Spent Nuclear Fuel Management in the Czech Republic:

Progress Concerning Deep Geological Repository Development

J. Slovak[1]

1. SÚRAO

I. INTRODUCTION

The Radioactive Waste Repository Authority (SÚRAO) is a state organisation established under § 26 of Act no. 18/1997 Coll., on the peaceful utilisation of nuclear energy and ionising radiation (the Atomic Act) and on amendments to certain other Acts.

SÚRAO's mission is to ensure the safe disposal of existing and future radioactive waste in compliance with the requirements of nuclear safety and human and environmental protection.

Upon the adoption of the Atomic Act the state assumed responsibility for the safe disposal of all radioactive waste in the Czech Republic. In accordance with this Act SÚRAO, as a state organisation, provides a variety of services relating to the safe handling of all types of radioactive waste and the coordination of research and development in the field of radioactive waste management including the deep geological repository development project.

II. SITE SELECTION PROCESS

Potentially suitable sites for deep repository construction were selected by the Czech Geological Institute in 1992. SÚRAO subsequently selected 6 sites situated in stable granite formations. Following the completion of this phase of the selection process, geological research work commenced at the sites in the second half of 2003 with the aim of collecting more detailed geological data in order to reduce the surface area of each candidate site. Work carried out before 2004 was considered geological research (in terms of Act 62/1988 on geological work practices). An evaluation of the work performed was completed in 2005. However, in view of the overwhelmingly negative public attitude to the project, SÚRAO, following agreement with the Ministry of Industry and Trade, suspended all geological work at the sites until 2009 (the Government, by means of Decision No. 550 of 2 June 2004, accepted the suspension). Consequently, sites were searched for with potentially more favourable public attitudes to the project. The investigation of former military areas was launched by SÚRAO at the end of 2008 in compliance with its plan of activities approved by the Government (Government Decision No. 1315 of 20 October 2008). The Boletice former military area was assessed in particular detail. In addition, an area close to a currently operational uranium mine at Dolní Rožínka (Kraví hora) was added to the list of candidate sites.

The site assessment stage will be concluded in 2018 with the evaluation of each site according to common criteria regarding the suitability of DGR siting, the repository's long-term safety, possible requirements concerning the potential impacts of the repository´s construction and operation on the environment as well as the socio-economic impact of the repository´s construction and operation on community development plans and the living conditions of local people. Work will continue on four preferred localities which will include a further investigation stage and a detailed examination of the suitability of the sites for the construction of the deep repository. The assessment stage at the four selected localities will aim at obtaining relevant knowledge of the rock haracteristics at the depth anticipated for repository construction with the objective of determining two candidate localities, one of which will be selected as the final locality and the other as a reserve locality for DGR siting. SÚRAO is working hard to meet the deadline set by the Concept of Radioactive Waste and Spent Nuclear Fuel Management in the Czech Republic, i.e. with concern to the identification of a final locality in 2025, the drawing up of a formal proposal accompanied by the positions of the communities concerned to be submitted to the Government for approval and an application for site protection at the preferred locality. Obtaining the relevant data from depths

anticipated for DGR construction depends not only on technical considerations but also on the granting of permission for the establishment of investigation areas at the localities concerned. Experience to date has shown that procedural issues will probably make up the key factor in terms of meeting the milestones set out in the Concept.

III. Research support for deep geological repository safety assessment

Detailed research on the phenomena, processes and events that may occur within the deep geological repository over thousands of years is essential to the understanding of their impacts on repository safety. This issue makes up one of the most demanding research tasks in terms of time and complexity. The aim of the pro-ject is to obtain the selected data, models, arguments and other information necessary for the evaluation of the long-term safety of potential sites for the deep geological repository.

This makes up one of a number of pilot projects in which SÚRAO is involved. The aim is to develop and optimise in detail the conceptual technical design of the disposal system and its individual components in such a way that is acceptable in terms of both operational and long-term safety, while incurring reasonable investment and operating costs.

IV. Underground research facility Bukov

Bukov URF construction commenced in 2013 and will be completed in 2017. Work to date included the driving of an access shaft with a total length of 300 metres, the building of the appropriate infrastructure and the preparation of support facilities for specialist scientific teams. In parallel with construction, the first stage of an experimental programme entitled the Complex Geological Characterisation of the Bukov URF Underground Facility is underway. The research programme is aimed at gathering the unique support data required for a description of the rock environment, the provision of information for the evaluation of potential DGR localities and the validation of rock environment description methodologies. The programme is made up of a number of parts, i.e. geological, hydrogeological, geotechnical and transport studies. The experimental programme to be carried out in future years reflects the Research and Development Plan prepared by SÚRAO for the period 2015 to 2025 and the various required parameters as evaluated in the site selection process.

V. Communication

SÚRAO´s objective is to increase the levels of mutual confidence and understanding, respect and social responsibility between SÚRAO and the public. An integral part of the future decision on candidate sites and the final site will consist of the acceptability of the future design by the affected communities. SÚRAO has always strived to deal with the municipalities concerned in an open and transparent way.

Public relations with respect to the currently operational Richard near Litoměřice, Dukovany and Bratrství near Jáchymov repositories primarily concerned the operation of local information centres, the distribution of information materials and regular meetings with local public representatives. Some information meetings are held as part of regular sessions held by so-called civil security committees (the Richard Civic Control Commission, Jáchymov Civic Control Commision and the Dukovany Civic Security Commission), while others are held at the request of local councils.

Direct communication with the public concerning the development of the deep repository focused mainly on the provision of information to the public on current geological investigation work carried out at the localities preselected as suitable for deep repository siting and within which investigation areas. The opportunity to meet with experts was again offered to local people in order for them to discuss any topic they found of interest and a number of local councils took advantage of this offer during the year.

Archaeology analogues for geological disposal of spent nuclear fuel (SNF) – current status and future outlook in Taiwan

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I. Introduction

This research on archaeological analogues is meant to advance our ability to predict the long term behavior of the copper canisters (shells) with cast iron inserts used in the deep-geological disposal of spent nuclear waste outlined in the KBS-3 concept design in Taiwan. The objectives of this study were to measure the thickness of corrosion products on the surface of unearthed bronze and ironware relics, and analyze the composition of the matrix and corrosion layer.

The relics (Figure 1) were unearthed at a depth of 3-4 m in a region of the Hanben heritage site, in Nanao Township, Ilan County, Taiwan. The excavation site (Figure 2) was discovered in March 2012 by personnel working on the Suhua Highway Improvement Project. The region has a humid subtropical climate with annual average temperature of 22.3℃, accumulated rainfall of 2827.7 mm, and evaporation of 400 mm. The artefacts were estimated to be between 1100 to 1800 years of age.

II. Experimental section

The chemical composition, corrosion products, and extent of corrosion were characterized using non-destructive testing methods, including elemental analysis using energy dispersive X-ray fluorescence (EDXRF, Horiba, XGT-5000), Raman spectroscopy (Horiba, Jobin Yvon), and micro-computerized tomography (Belgium SkyScan 1076 in-vivo micro-CT), respectively. Soil tests on moisture, pH, and conductivity were respectively conducted in accordance with S280.62C, S410.62C and S102.63B standards. The chemical composition of the soil was examined using a wavelength dispersive X-ray fluorescence (WD-XRF) spectrometer (Kxios, PANalytical Inc) and the anionic concentration was measured using an Ion chromatography system (Dionex ICS-5000, ThermoFisher Scientific).

III. Results

The moisture content of the soil was 24.8%, the pH was 7.12, and the conductivity was 335 μs/cm. The anionic concentrations of Cl^-, SO_4^{2-}, and CO_3^{2-} were 3.23,11.23, and 5.52 ppm, respectively. The chemical composition as determined by XRF was as follows: 54.78% SiO_2, 14.22% Al_2O_3, 3.16% MgO, 9.39% Fe_2O_3, 1.63% Na_2O, 4.40% CaO, 1.96% K_2O, 1.04% TiO_2, 0.17% MnO, 2.40% P_2O_5, LOI 7.85%.

Fe was shown to be the major constituent (>90 %) of the ironware and iron hook. The samples present crystalline phases of hematite (α-Fe_2O_3) and magnetite (Fe_3O_4) in the outer layers as well as small quantities of goethite (α-FeOOH) in the inner layer. The bronze adornments are composed of Cu (20%), Sn (50%), and Pb (30%). The bronze bell is composed of Cu (50%), Sn (20%), and Pb (12%). Most of the corrosion product in the bronze is malachite, cuprite, cerussite, and small quantities of atacamite.

Grayscale images obtained from micro-computed tomography (micro-CT) scans indicate potential changes in the density or pore distribution of the sample material (Figure 3). These findings may facilitate efforts to estimate the rate of corrosion in these relics. They also have implications for evaluating the lifetime of copper canisters and cast iron inserts used in the storage of spent nuclear waste, based on the repository conditions outlined under the SKB KBS-3 concept. Archaeological data in this study (Table 1) was consistent with Japanese H12 and H17 safety assessments (JNC 2000 and 2005).

This analysis also supports the results of safety assessments pertaining to a proposed deep geological disposal facility in the area.

IV. CONCLUSIONS

Our conservative estimates for the corrosion rates of ironware (0.7-4.0 μm/a) and bronze artefacts (0.075-0.833 μm/a) are consistent with those in the literature. This demonstrates the efficacy of using 3D image reconstruction software based on micro-CT scans for the analysis of corrosion behavior. The humid subtropical climate in the Hanben heritage site is more geochemically active (more oxidizing) than what would be encountered in most of the host rock sites proposed for a deep repository. Nonetheless, it provides a valuable reference by which to predict the performance of the waste packages in geological repositories and provides qualitative indicators to facilitate the explanation of safety assessments to the public. Our findings attest to the efficacy of the proposed engineered barrier system.

V. FUTURE WORKS

Future studies will focus on the following areas of research: (1) measuring the thickness of corrosion layers of unearthed bronze and ironware relics (i.e., destructive analysis using FIB, EPMA, SIMS, or SEM/EDS) in order to obtain cross sections (depth profiles) for further study into the structure of the corrosion layer and underlying mechanisms; (2) interpretation of the relationship between the corrosion process and the environment in which the relics were buried/preserved; (3) formulation of a geochemical model (e.g., PHREEQC or EQ3/6) pertaining to the corrosion process of unearthed bronze relics.

Figure 1. Unearthed relics of ironware and bronze

Figure 2. Excavation site

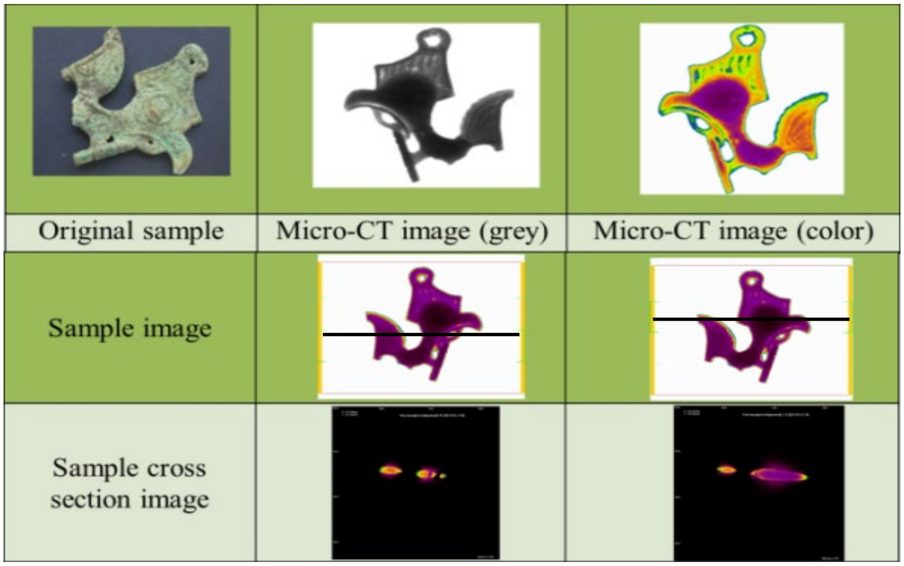

Figure 3. Micro-CT scans of bronze adornments

Table 1 Comparison of copper corrosion depths cited in safety assessment H12 (JNC 2000) with existing and new archaeological analogue data

Form of data		Corrosion depth (per 1000a)	Reference	Buried environment
Archaeological analogue (Taiwan)	Ironware	1.0~2.7mm	SNFD-05-IPR-002-02 Natural Analogue Research in Taiwan for Final Disposal	Iron artefacts in soils
	Iron hook	0.7~4.0 mm		
	Bronze adornment	0.075~0.833 mm		Bronze artefacts in soils
	Bronze bell	0.198~0.671 mm		
Short-term lab		13 mm	JNC (2000a)	Uniform corrosion of copper
Archaeological analogue		<3 mm	Range of studies cited in JNC (2000a)	Uniform corrosion of copper and bronze
Archaeological analogue		0.26–39 mm	Bresle et al. (1983)	Pitting corrosion of copper
Archaeological analogue		0.025–1.27 mm	Tylecote (1979), Johnson & Francis (1980)	Uniform corrosion of mixed artefacts
Archaeological analogue		0.15 mm	Hallberg et al. (1987)	Kronan cannon
Archaeological analogue		0.13–1.13 mm	Appendix D in IAEA (2005)	Bronze artefacts from a river
Archaeological analogue		<0.27 mm	Appendix D in IAEA (2005)	Bronze artefacts in soils
Archaeological analogue		0.4–1.2 mm	Appendix D in IAEA (2005)	Copper artefacts in flood plain soil
Archaeological analogue		0.01–1.91 mm	Appendix D in IAEA (2005)	Bronze artefacts in flood plain soil

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