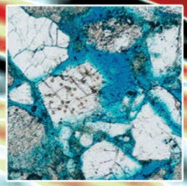 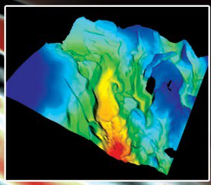 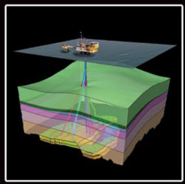

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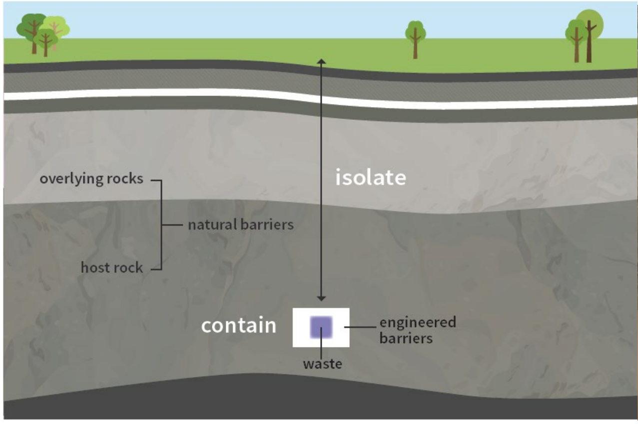
ABSTRACT BOOK

Geological Disposal of Radioactive Waste

4th-6th June 2024
Department of Earth and Environmental Sciences, Williamson Building, The University of Manchester, M13 9PL, Manchester, UK



Providing safe, permanent disposal of legacy and future higher activity radioactive waste is essential. Deep burial of waste in a Geological Disposal Facility (GDF) is the internationally recognised preferred way forward.

Delivering a GDF requires the input from a range of expertise including geoscientific, environmental, social scientific and engineering disciplines:

- to develop an understanding of the surface, near-surface and deeper geological history – the pre-disposal 'baseline' conditions at any proposed site;
- to understand (through surface-based investigations, natural analogue studies, modelling and experimentation) how the sub-surface environment may respond to GDF construction and waste emplacement; and
- to understand how the disposal system (engineered barriers, host and surrounding geology, surface environment) may evolve on a timescale that could extend to one million years in the future.

This conference welcomes contributions relevant to the geological disposal of radioactive waste. It will seek to encourage links between geoscience, environmental sciences, social sciences and engineering, in the context of international progress in the development of GDFs. Case histories, ongoing collaborative work and planned activities to enhance the state-of-the-art will be considered. Opportunities for closer working of various technical communities in relation to geological disposal will be discussed and promoted as appropriate.

Technical workshops will be offered on 6th June 2024.

For further information please contact:
The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Email: energygroup@geolsoc.org.uk

Convenors:

Simon Norris
NWS, *University of Manchester & EGC*

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Geological Disposal of Radioactive Waste

4th-6th June 2024

Hybrid Conference, University of Manchester and Zoom, BST

Final Programme

Day One	
08.30	**Registration**
09.15	**Welcome – University of Manchester & Geological Society**
09.25	**Introduction – Conference Aims, Ways of Working** Simon Norris, *Nuclear Waste Services*
	Session One: POTENTIAL HOST ROCK CHARACTERISATION
09.40 Pre-Recorded	**Investigating the Reproducibility and Reliability of Multiscale Fracture Characterization** G. Amicarelli, *Newcastle University*
09.55	**Advancing techniques for Microscopic to Mesoscopic Gas Migration in Clay Rock (LSSRs): Deep Learning for Long-Term Management of Deep Geological Disposal** Abdelrazik Elfar
10.10	**Characterising the subsurface geology of potential Geological Disposal Facilities using elemental and mineralogical geochemistry** Alexander Finlay, *X-Ray Mineral Services Ltd*
10.25	**BREAK**
11.10	**Advancing Geological Disposal Facility Design through Digital Outcrop Modelling** David Hodgetts, *VRGeoscience Limited*
11.25	**Inversion feasibility study to characterise the Mercia Mudstone Group, Copeland area** Ana Somoza Graterol, *Cegal*
11.40 Virtual	**Tectonic setting of the site selected for a Deep Geological Repository in Switzerland: insights from 3D seismic interpretation** Miller Zambrano, *University of Camerino*
11.55	**Poster 'Elevator Pitches'** **All 11 poster lead authors to give a 2 minute introduction to their poster, max 2 slides** Cam Fletcher, Simon Schneider, Jonny McEvoy, Elliott Bird, Sam Jones, Lie Kong, Olatundun Aihie, Lucky Oseghale Odiase, Matthew Kirby, Kathryn Page, Qian Zhang
12.30	**LUNCH**
13.45	**POSTERS SESSION**
14.15 Virtual	**KEYNOTE: Decision on the Site for Switzerland's Geological Disposal Facility for Radioactive Waste** Tim Vietor, *Nagra*

15.00	**BREAK**
	Session Two: UK SITE CHARACTERISATION
16.00	**New Data reveals Hidden Complexity Offshore Cumbria: Importance of High-Resolution Seismic Reflection Data in Ground Modelling for Nuclear Waste Disposal** Neil Jones, *Jacobs*
	Session Three: SITE EVOLUTION & ASSESSMENT STUDIES
16.15	**New assessment workflow for borehole closure for the Final Ultra Deep Disposal (FUDD) concept in sedimentary formations** Gert-Jan Heerens, *TNO – Geological Survey of the Netherlands*
16.30	**Final Ultra Deep Disposal: Geological Assessment of Borehole Storage in Sedimentary Basin Settings** Rixt Altenburg, *TNO – Geological Survey of the Netherlands*
16.45	**Future geological evolution and effects on deep disposal of radwaste in the Netherlands** Johan ten Veen, *TNO- Geological Survey of the Netherlands*
17.00	**End of day one**
17.15 - 18.15	**Drinks Reception**

Day Two

08.15	**Registration**
	Session Four: ANALOGUE STUDIES
08.45 Virtual	**The relevance of natural analogues to the German site selection procedure** Milena Schoenhofen-Romer, *BGE mbH*
09.00	**International Bentonite Longevity (IBL) project: an overview** W.R. Alexander, *Bedrock Geosciences*
09.15	**The engineering properties of low strength sedimentary rocks – Evidence from the construction of the High Speed Two railway** K.M Briggs, *University of Bath*
09.30	**Multiscale-multiproxy seal assessments of Mesozoic mudrock units in North Yorkshire, a potential aid to screening and modelling radioactive waste disposal facilities** Colm S. Pierce, *CASP*
09.45	**Contribution of programming language to novel mine risk assessment project** Mabe Fogang Pieride, *Liaoning Technical University, PR China*
10.00	**New insights into the Muhos Formation, an unmetamorphosed Mesoproterozoic sedimentary rock sequence in central Finland** Heini Reijonen, *Geological Survey of Finland*
10.15	**BREAK**

10.45 Virtual	**KEYNOTE: Perspective on French Geological Disposal Programme** Frédéric Plas, *ANDRA*
	Session Five: GEOMECHANICAL STUDIES
11.15	**Some geotechnical considerations for nuclear waste disposal in the Mercia Mudstone Group** Kieren Quigley, *Mott MacDonald*
11.30	**Assessing the Fracturing Mechanisms and Evolution of the Excavation Damage Zone of Underground Structures in Hard Rockmasses for Disposing Nuclear Waste** Ioannis Vazaios, *Ove Arup & Partners Ltd*
11.45	**Modelling of Spalling around Deposition Boreholes in a Geological Disposal Facility for Nuclear Waste** Robert Zimmerman, *Imperial College London*
12.15	**Modelling Techniques for Simulating the Excavation Damage Zone around Deep Underground Excavations** Anastasios Stavrou, *WSP UK Ltd*
12.30	**LUNCH**
	Session Six: TRANSPORT PROCESSES (Part 1)
13.45	**Evidence of gas migration processes in Opalinus Clay; The Gas Transport (GT) field study conducted at the Mont Terri Underground Research Laboratory** Qian Zhang, British Geological Survey
14.00	**Multi-phase flow modeling at the component level for the Swiss deep geological repository** Chao Li, *INTERA*
14.15	**Diffusion measurements in natural and synthetic rocks: lessons learned and some relationships identified** Jon F. Harrington, *British Geological Survey*
14.30	**Evidence of rock matrix diffusion from forty years of site investigations in Finland and Sweden** P. Trinchero, *Amphos 21*
14.45	**Understanding the pore structure of mudrocks for predicting porosity, flow, and transport in host rocks for radioactive waste disposal** Andreas Busch, *Heriot-Watt University*
15.00	**BREAK**
	Session Seven: WASTEFORM/ WASTEFORM EVOLUTION
15.30	**The Evolution of the Supply of Cementitious Materials used to Encapsulate Intermediate Level Radioactive Wastes and Implications for the Geological Disposal Facility** G.M. Cann, *National Nuclear Laboratory*
15.45 Virtual	**Discrete event simulation of spent fuel assembly packaging into disposal canisters for the purpose of deep geological disposal** Andreas POLLER, *CSD Engineers AG*
16.00	**Will sizing down scale up the problem? A perspective on how waste arising from PWR SMRs and BWR SMRs could impact future disposability** Emma Nickels and Amirah Azhar, *AtkinsRéalis*
	Session Eight: RELATED INITIATIVES
16.15	**RSO presentation** Prof Sam Shaw, *University of Manchester*

16.30	**INFORM presentation** Lie Kong, *University of Manchester*
16.45	**End of day two**

Day Three	
08.15	**Registration**
	Session Nine: MONITORING
08.45	**Confidence in Repository Monitoring Data - Key Results from the MODATS Work Package of EURAD** Thomas Haines, *Galson Sciences Limited*
	Session Ten: ENGINEERED BARRIER SYSTEM
09.00	**Hydromechanical behaviour of bentonite clay at temperatures greater than 100°C** Caroline C. Graham, *British Geological Survey*
09.15	**Interaction of simulant thermally-treated intermediate level wastes with a high pH cementitious backfill** Graham Kenyon, *Jacobs*
09.30	**Bentonite homogenisation and swelling: The effect of salinity** K. A. Daniels, *British Geological Survey (now University of Cardiff)*
09.45	**Long-term Thermal-Hydrological-Mechanical Behaviour of Bentonite as a Component of Radioactive Waste Disposal Concepts** Tom Mitchell, *University College London*
10.00	**KEYNOTE: Regulating a geological disposal facility and the importance of geological knowledge in the underpinning regulatory submissions** Candida Lean, *Environment Agency*
10.30	**BREAK**
	Session Eleven: TRANSPORT PROCESSES (Part 2)
11.00	**Thermal-hydro-chemo-mechanical coupled modelling of ionic transport in clay materials** Qingrong Xiong, *Shandong University*
11.15	**A review of the state of the art in redox and kinetics applied to nuclear waste disposal facilities** Eli Colas*, Amphos 21 Consulting S.L*
11.30 Virtual	**Buoyancy-Related Groundwater Flows: Comparing the Physics of Hydrothermal and Radwaste Situations** Gary D Couples and Helen Lewis, *Heriot-Watt University*
11.45 Virtual	**Thermo-Hydro-Mechanical (THM) Design of Finnish Spent Nuclear Fuel Repository** Erdem Toprak, International Center for Numerical Methods in Engineering (CIMNE)
12.00	**Nano-scale imaging and modelling of gas transport in clay-rich mudstones** Xin Zhong, University of Manchester
12.15	**PANEL SESSION**
12.50	**Closing Remarks**
13:00	**LUNCH**
14:00	**End of Conference**

Posters
Observing and quantifying deformation behaviours in halite for applications in compressed air energy storage (CAES) Cameron Fletcher, *British Geological Survey*
The Triassic Mercia Mudstone Group as a host rock for radioactive waste: insights from a continuous core succession in North Yorkshire Simon Schneider, *CASP*
The influence of depositional and diagenetic heterogeneity on fracture distributions in the Mercia Mudstone Group Jonathon McEvoy, *University of Liverpool*
Evolution of bentonite pore water chemistry upon resaturation with saline groundwater Lucky Oseghale Odiase, *University of Plymouth*
Adapting disposal concepts to reflect emerging UK geological environments Matthew Kirby, *Nuclear Waste Services*
Using analogue tests to observe fundamentals of gas flow in clay-rich rocks and barrier systems Elliot Bird, *British Geological Survey*
Controls on the Gas Permeability of the Triassic Mercia Mudstone Group, UK Samuel Jones, *University of Liverpool*
Characterisation of Mercia Mudstone Containing Mineralised Fractures Junlong Shang, *University of Glasgow*
Excavation Disturbance Zone Evolution in UK Jurassic and Triassic Mudrocks – Implications on fluid flow in a nuclear waste repository Olatundun Aihie, *University of Plymouth*
Conceptual workflow for coupled hydro-chemical-mechanical analysis of mudstone based fault zones Kathryn Page, *Heriot Watt University*
Manufacturing and geotechnical characterisation of synthetic samples for engineered barrier system in radioactive waste repositories Qian Zhang, *British Geological Survey*

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CONTENTS PAGE

ORAL ABSTRACTS
(In Programme Order)

Session One: POTENTIAL HOST ROCK CHARACTERISATION

Investigating the Reproducibility and Reliability of Multiscale Fracture Characterization

G. Amicarelli1, M. T. Ireland2, C. T. Davie1*
1School of Engineering, Newcastle University, Newcastle upon Tyne, UK
2School of Natural and Environmental Sciences, Newcastle University, Newcastle upon Tyne, UK
**Corresponding author (e-mail: G.amicarelli@newcastle.ac.uk)*

Faults and fractures are crucial factors in geological disposal facilities because they affect storage and fluid flow. These geological features can both enable and inhibit fluid movement (Miranda et al., 2020). This dual role has significant implications for the structural integrity of the facility, as well as for the potential pathways of contaminants. This is especially relevant for rocks with low matrix permeability, where the behavior of faults and fractures plays a pivotal role in fluid dynamics (Berkowitz, 2002).

In this work we have investigated the reproducibility and reliability of multiscale fracture characterisation from outcrops, specifically evaluating 1) the reproducibility and reliability of automated fracture extraction from decimeter resolution aerial by comparing two methods, across four different outcrops and 2) the differences in fracture networks characteristics from imagery with resolution between 0.002m/px to 0.2m/px by interpreting fracture networks from three different resolution datasets across the same area.

Our findings indicate 1) the reliability of methods is significantly influenced by the original image properties, particularly the contrast between fractures and the surrounding rock mass; 2) extracted networks are sensitive to the parameterisation of extraction methods and should be evaluated carefully to determine appropriate settings; 3) multiscale analyses underscore the importance the surface expression of fracture width, which is essential for correctly identifying and tracing fracture networks; ; 4) at lower resolutions fracture networks may be oversimplified, while as a result of higher resolution data being often limited in extent, longer length scale features may be missed.

The work demonstrates that reliable and reproducible characterisation of fracture networks from outcrop require a careful evaluation of the image properties, including the pixel characteristics of both the fractures and rock mass, ahead of interpretation as well as an understanding of the parameters used for selectively mapping fractures.

Advancing techniques for Microscopic to Mesoscopic Gas Migration in Clay Rock (LSSRs): Deep Learning for Long-Term Management of Deep Geological Disposal.

Abdelrazik Elfar[1], Dr Masoud Babaei [1], Dr Lin Ma[1], *Professor Simon Norris[2], Dr Andrew Cooke[2]*
Email: abdelrazik.elfar@manchester.ac.uk

Clay-rich host rocks (or lower strength sedimentary rocks) are highly desirable formations for a Geological Disposal Facility (GDF) due to their low permeability and favourable geochemical properties that help to reduce the migration of aqueous and gaseous radionuclides. However, large volumes of hydrogen gas may be generated within a GDF from container corrosion and a range of other waste degradation processes, which may generate large gas pressures if contained by a low permeability host rock. Therefore, accurate prediction and understanding of the gas migration process within the GDF and surrounding formations are fundamental to ensure long-term safe storage of nuclear waste disposal. Complex methods have been established to handle relevant phenomena effectively at the microscale. However, there is currently a lack of studies linking micro-scale behaviour to larger scales that govern bulk gas migration though clay-rich host rocks, thereby limiting predictability. Multiscale gas transport modelling aims to address such challenges by integrating meso-scale (cm) and micro-scale (nm to mm) physical and chemical processes.

Advanced imaging techniques play a pivotal role in analysing gas transport properties at various scales. The need for employing deep learning methods arises from the necessity to incorporate uncertainty as well as optimize computational time when large samples are considered. At the micro scale, the generation of additional images featuring diverse mineral distributions enhances uncertainty quantification. Simultaneously, at the meso scale, this approach serves to mitigate the computational costs associated with domains that include long-range spatially correlated features.

In this work, TOUGH2 and COMSOL software packages have been used for the meso (cm) scale and micro-scale simulations, respectively. This study evaluated microscale simulation results, highlighting the significance of hydrogen diffusion in the aqueous phase, the diffusion transport of gas in clay formations at the micro-scale was investigated using single-phase modelling in COMSOL. The micro-scale model will generate an “overall diffusion coefficient” for upscaling. Subsequently, mesoscale simulation results were assessed over approximately 200 years, with a specific focus on two-phase flow using TOUGH2.

At the micro-scale modelling, we considered the clay mineralogy and its heterogeneous distribution to determine the overall diffusion coefficient (Doe). The magnitude values for the effective diffusion coefficient "input" for clay minerals span a range of 10-10 m^2 s^(-1).The mesoscale investigation involved conducting sensitivity analyses for two models, each employing the Doe obtained through numerical and experimental methods. The results indicated an inverse relationship between the diffusion coefficient and gas pressure accumulation. Remarkably, the numerical model demonstrated a reasonably good agreement with experimental results obtained from Boom clay samples. Furthermore, the observed gas pressure is attributed to the accumulation of hydrogen near canister, which may lead to the onset of advective gas flow mechanisms, which may be detrimental to the host rock properties.

Characterising the subsurface geology of potential Geological Disposal Facilities using elemental and mineralogical geochemistry.

Alexander Finlay[1], Andrew Wiseall[2], Jesal Hirani[1], Paul O'Neill[1]

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2 Nuclear Waste Services, London, UK

The understanding of subsurface geology is key to the development of geological disposal facilities (GDFs) for radioactive waste. Nuclear Waste Services is currently in the process of characterising potential sites for a UK GDF. The only available current sub-surface physical samples from these sites come from legacy onshore boreholes and offshore oil and gas wells. The majority of recovered geological material takes the form of drill cuttings, with core or side wall core being highly limited. Drill cuttings can provide useful information on the geology of the subsurface, however, before this work is undertaken the quality of the cutting material needs to be checked as cuttings are comprised of mixed lithological material collected typically over a 2-10 metre intervals from up to hundreds of metres below the seabed. This means that recorded depths may not be correct, they may contain caved material, there may be a bias in recovery of different lithologies and material may be lost during sample washing-Through several steps, as will be discussed, this work has have aimed to quantify uncertainties associated with these factors, as well as making alterations to recorded depths if necessary. Cuttings are collected wet meaning that sample bags normally contain drilling mud, which may sometimes form the majority of a sample bag leading to only a small volume/mass of geological material being recovered. Furthermore, samples form historic oil and gas wells may have undergone multiple different historic analysis meaning that only small masses of material are left, necessitating that any current analysis is carried out to maximise the information gained from the minimum amount of destructive analysis possible.

This paper will present a new workflow devised by X-ray mineral services (XMS) and Nuclear Waste Services (NWS) that both demonstrates how representative cuttings are of the subsurface and enables the production of both accurate and precise quantitative elemental, mineral and geological data from small cutting sample masses. Having greater confidence in this data will allow us to draw greater conclusions in terms of quantifying the properties of the sub-surface, for example the percentage of clay minerals present in the sub-surface, which is an important factor in allowing these rocks to act as barriers. This will be demonstrated through a series of clastic, carbonate and evaporite case studies from the potential Copeland and Theddlethorpe siting areas.

The new workflow utilises Inductively coupled plasma mass spectrometry and inductively coupled plasma - optical emission spectrometry (ICPMS & ICP OES) to provide high precision, low limit of detection elemental data on small (~1g) masses of material. The Potassium, Thorium and Uranium concentrations from this data is then utilised to calculate a chemical gamma ray response which is compared to wireline gamma to understand how representative the sample is to subsurface geology of the same depth. As well as acting as a double check for depth validation, having a good agreement on the 'chemical gamma ray' gives us confidence that the cuttings sample (albeit very small) is representative of the depth interval being sampled (again albeit averaged over a depth range similar to the resolution of the wireline tool).

The ICP analysis undertaken in this workflow provides data for ~50 elements and so, in addition to producing the Chemical gamma ray, can also be used to provide a quantified “chemical lithology” for the analysed cuttings. For example, Silica is predominantly found in Quartz and Aluminium in clay minerals, therefore the Si/Al value acts as a proxy for grain size and the sand/clay composition of an analysed sample and the Calcium content can act as a proxy for carbonate content. This method is used to define every analysed sample as being either a calcareous or dolomitic (if appropriate) claystone, siltstone, argillaceous sandstone, sandstone, salt or carbonate. As this method uses set defined values it is consistent across any analysed sample, enabling quantitative lithological comparison to be undertaken.

When poor agreement between the calculated chemical gamma ray and the downhole measured values this gives us less confidence in the cuttings samples being representative of the depth range being sampled. There are a number of reasons for which this may occur, for example if there are significant amounts of caved material present. The flexibility of the ICP analytical approach will be further demonstrated as the low level (part per million) trace elements data provided by the ICP analysis can still be utilised to provide some information on the subsurface geology. When samples have been shown to be representative of the sampled depth range, i.e. show good agreement with wireline gamma, a subset of samples with greater mass are analysed by X-ray diffraction (XRD) to provide quantitative mineralogy, including the key less than 2µm clay fraction. As this quantified XRD cannot be undertaken on small masses of cutting samples, the XRD results are utilised to produce a training dataset to enable the mineral modelling of all ICP data, ensuring that a “chemical minerology” can be produced for all samples that have undergone ICP analysis.

This presentation will present a number of small-scale case studies from currently on-going work, whilst also demonstrating the value and potential of analysing small quantities of cuttings samples. The workflows developed as part of this project have enabled both XMS and NWS to begin to understand the geologies present in the potential siting areas, data from this project will be combined with other available data sources (for example petrophysical data), to begin to understand the geology in more detail.

Advancing Geological Disposal Facility Design through Digital Outcrop Modelling

Authors: **David Hodgetts**[1,4], William Head[2,4], Brian S. Burnham[3,4]

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[2] *Westinghouse Electric Company. UK*

[3] *Independent Geologist. Derbyshire, UK*

[4] *Formerly @ Department of Earth and Environmental Sciences, University of Manchester, UK*

Digital outcrop models (DOMs) are pivotal in both the site selection and design processes for Geological Disposal Facilities (GDFs). Utilising high-resolution DOMs, derived from photogrammetry and lidar technologies, allows for comprehensive analysis of geological structures at prospective GDF locations. These analyses encompass lithological and hydrological aspects, and structural integrity assessments, thereby yielding more accurate geological evaluations.

The integration of DOMs with geotechnical engineering and geological insights is crucial for refining geological predictions, which in turn optimises GDF designs. This leads to safer and more environmentally sustainable practices in radioactive waste management.

DOMs provide detailed and accurate depictions of geological formations, enhancing the understanding of complex geological heterogeneity. Identifying features such as faults, fractures, and bedding planes is essential for assessing site stability and suitability. Given that the host rocks of a GDF are underground and not directly visible, DOMs enable predictions about geological heterogeneity based on observed surface data from outcrop analogues. This surface data is then utilised to populate subsurface models for GDF design.

High-resolution DOMs enable more extensive geological data collection than traditional geological mapping methods, critical for detailed GDF site characterisation. Importantly, DOMs provide access to key outcrops that may be otherwise unreachable, enhancing data collection and improving the statistical significance of datasets. Furthermore, DOMs allow for the simulation of various geological scenarios, aiding proactive design and risk management.

DOMs reduce the need for extensive fieldwork, offering a cost-effective and time-efficient approach to geological investigation. By bringing the outcrop into the office virtually, more time can be allocated to quantitative data collection. Furthermore, the digital storage of outcrops enables multiple users to interrogate the data, enhancing quality control and reproducibility of results.

DOMs foster collaboration among geologists, engineers, and environmental scientists, ensuring a holistic approach to GDF design. This collaboration is facilitated through virtual reality, desktop visualisation, and a blend of virtual and field-based methods. DOMs transform complex geological data into visual formats, aiding in comprehension across various disciplines. For instance, a geologist's detailed knowledge of rock formations can be visualised for easy interpretation by engineers or environmental scientists. This visual representation aids in bridging the gap between differing scientific languages and methodologies, leading to a more integrated approach to GDF design and management.

Digital models are effective tools for communicating key geological aspects of GDF sites to the public and stakeholders, promoting transparency and trust. Stakeholder engagement, involving local communities, regulatory bodies, and environmental groups, benefits from digital models as focal points for discussion. These models enable stakeholders to visualise the potential impacts and safety measures of a GDF, encouraging active participation and informed decision-making. The use of digital models in public engagement sessions underscores a commitment to transparency, and building trust with the public and stakeholders, especially crucial given the common public scepticism about GDF projects due to safety and environmental concerns. Digital models address misconceptions and concerns effectively, simulating scenarios including long-term safety and environmental impact assessments, and providing evidence-based responses to common queries.

Digital outcrop models are integral to GDF design, offering improved accuracy, efficiency, and safety in the evaluation and management of geological disposal sites. By good choice of outcrop analogues and effective interpretation, visualisation and analysis the application of digital outcrop models can play an important role in site selection, GDF design and construction, as well as long-term predictions and monitoring of GDF behaviour.

Inversion feasibility study to characterise the Mercia Mudstone Group, Copeland area

Ana Somoza Graterol, *Cegal* (*ana.somoza.graterol@cegal.com*); David Eastwell, *Nuclear Waste Services* (*David.Eastwell@nuclearwasteservices.uk*)

Nuclear Waste Services collaborated with Cegal to undertake a seismic inversion feasibility study on the Mercia Mudstone Group (MMG) in the Copeland area. This work was undertaken in support of ongoing site evaluation studies executed under the auspices of the Copeland Mid and South Community GDF Partnerships.

This study focussed on assessing the applicability of modern seismic inversion methods to discriminate the alternating mudstone, dolostone, halite, anhydrite and gypsum beds within the Lower Triassic Mercia Mudstone Group and the secondary Sherwood Formation, and to model their bulk rock elastic properties. To achieve this, Cegal undertook a multifaceted investigation utilising a database of 15 legacy wells with associated log sets, 10 of which recently underwent updated petrophysical evaluation by RPS Group.

The well data were QC'ed and conditioned using Rock Physics Models calibrated to end-member lithologies using the Gardner relationships for Rho-Vp and Greenberg-Castagna relationships for Vs-Vp determination.

Using these conditioned logs, initial multi – parameter facies cross-plotting, including Vp-Rho, Vs-Vp, Vp-PHIE cross-plots coloured by different lithology volume logs, porosity and water saturation, was performed at both well log and seismic scale to aid acoustic facies discrimination between the MMG and the Sherwood sandstone Formation, as a secondary objective. At both scales it was found that a clear separation between mudstone, halite and anhydrite could be made within the MMG. In the Sherwood Sandstone, identifiable facies comprised brine sands, gas sands, mudstones and, occasional anhydrite in a certain wells.

More detailed Extended Elastic impedance (EEI) and Vp/Vs-AI analysis was then carried out to understand the separation in the context of possible model or facies based seismic inversion routines, including that of Cegal's One Dimension Stochastic Inversion approach, which relies on colour inverted EEI volumes as input. It was shown that appreciable separation could be achieved in all except the elastically overlapping MMG Halites and Sherwood Brine Sands, which may require to be separated into distinct inversion layers with intervening surface interpretation.

Finally, tuning analysis was performed using 2D wedge models for different scenarios: mudstone/halite/mudstone, and halite/mudstone/halite and using interpolated log data and average values of Vp, Vs and Rho. The analysis showed that, to be able to seismically identify halite, the minimum bed thickness should be approximately 6ms. For the mudstones, the minimum bed thickness should be 22ms. Halite and mudstones thinner than these thresholds would not be seismically distinguishable.

Tectonic setting of the site selected for a Deep Geological Repository in Switzerland: insights from 3D seismic interpretation

Miller Zambrano[1], Stefano Mazzoli[1], Jon Mosar[2]

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Following extensive geological, geophysical, and drilling campaigns, the site for a Deep Geological Repository (DGR) in Switzerland was identified at the easternmost termination of the Jura Mts (in an area comprised between the villages of Schöfflisdorf and Eglisau). An overconsolidated Aalenian shale, the Opalinus Clay (dated at ca. 175 Ma), was selected to host such a DGR. Using 3D seismic data, we document the tectonic setting of the siting region (Nördlich Lägern). This is characterised by the occurrence of two ENE trending fold-thrust zones involving the Triassic-Jurassic epicontinental platform succession and the stratigraphically overlying Cenozoic Molasse Basin deposits. The location of both fold-thrust zones appears to be controlled by variable interaction between the detachment level hosted in the Triassic evaporites of the Muschelkalk Group and normal faults linked to an underlying Permo-Carboniferous half-graben. The northern fold-thrust zone, manifested at the surface by the Siglisdorf anticline, consists of a ~ 2 km wide pop-up produced by thin-skinned thrusting. Although this structure is located above a step produced by an antithetic fault of the underlying Permo-Carboniferous half-graben, the integrity of the detachment appears to be preserved along the entire along-strike extension of this structure. The southern fold-thrust zone (located along the so-called Baden-Irchel-Herdern Lineament; BIHL) consists of multiple thrusts and backthrusts forming a series of fish-tail structures arranged in a narrow, steep belt involving the Mesozoic strata. A stronger interaction with sub-detachment faults is apparent at this location. Here, reverse faults propagated from the underlying Permo-Carboniferous basin fill into the overlying Mesozoic succession, probably as a result of mild basin inversion. Salt mobility and associated salt weld development may have further contributed to a degraded quality of the detachment at this location. In synthesis, different degrees of interaction between the evaporite detachment and underlying inherited faults produced a marked contrast in structural style (pop-up and triangle zone geometry) between the northern and southern fold-thrust zones.
Mild basin inversion appears to have produced both localised deformation and gentle folding also in the central part of the seismic volume, along the so-called Weiach-Glatfelden-Eglisau Lineament (WGEL). The latter, including inherited, reactivated Late Paleozoic faults and reverse fault splays offsetting the Near Base Mesozoic Unconformity, appears to represent a hinge zone between two regional rock panels (N and S of it) characterized by slightly different angles of dip. The 'undisturbed' (at the seismic scale) rock panel occurring between the BIHL and the WGEL was selected as DGR siting area. Based on seismic interpretation, such a rock panel is inferred to have undergone: (i) limited (of the order of a few hundreds of metres) 'en-masse' displacement by thin-skinned thrusting (controlled by the Triassic evaporite detachment and manifested by the development of the northern fold-thrust zone); and (ii) minor (of the order of a few percent) homogeneous shortening during mild basin inversion. The related internal strain of such an 'undisturbed' rock panel is recorded by small-scale deformation features observed in drill cores.
Understanding the tectonic evolution and the structural complexity is a critical step to identify undisturbed areas, thus unlocking best site locations for DGR placement.

KEYNOTE - Tim Vietor

Decision on the Site for Switzerland’s Geological Disposal Facility for Radioactive Waste

Tim Vietor & Nagra’s Site Selection Team

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Geological disposal is the only way to permanently protect humans and the biosphere from the radiological risks of radioactive waste. Emplaced deep below the earth’s surface, a geological disposal facility isolates the waste from the biosphere. A suitable host rock retains waste products that can escape the engineered barriers and allows radionuclides to decay in the geological barrier. Stable geological conditions prevent the creation of new pathways that could bypass the multi-barrier system.

The site selection process started in 2008 with a blank map of Switzerland and used a set of 13 safety criteria to successively screen out less suitable regions and sites. Nagra eventually identified three potential siting regions for a geological disposal facility. These three remaining siting regions have been investigated in detail from the surface and in 2022, Nagra announced the most suitable siting region, Nördlich Lägern, which is located slightly north of Zürich. Here, the spent fuel from the five nuclear power plants as well as their operational and decommissioning waste will be disposed of. A general license application will be submitted for this site in 2024. Currently, Nagra is completing the documentation for the application.

The talk will highlight the safety concept with emphasis on the role of the geological situation. The geological arguments for the choice of the site (oldest groundwater, largest amount of space and best long-term stability) will be presented in detail as well as the challenges and lessons learned in the site investigations.

Session Two: UK SITE CHARACTERISATION

New data reveals hidden complexity offshore Cumbria: Importance of high-resolution seismic reflection data in ground modelling for nuclear waste disposal

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The UK's Low-Level Waste Repository (LLWR) is situated on the Cumbrian coast adjacent to the Irish Sea. To ensure the long-term safety of any nuclear waste at this facility a detailed subsurface characterisation is required. Jacobs have investigated a proprietary, borehole-constrained ultra-high-resolution seismic reflection (UHRSR) survey, which has provided unparalleled insight into the evolution of the Quaternary geology of the region.

Although evidence of glaciation is prominent in previously published seismic reflection data, the higher resolution of the UHRSR dataset enables well-defined and traceable structures to be identified, providing new insights into the complex, polyphase nature of glacial deformation and erosion in the region. Variation in seismic reflectors typical of cyclic glacial sediments in addition to the erosional and deformational structures indicate the occurrence of at least three distinct glaciation events. Specifically, a previously unknown tunnel valley has been identified adjacent to the coastline running broadly parallel to other previously identified tunnel valleys like the Coulderton Channel. Two distinct channel-fill sequences are observed within the tunnel valley, providing evidence of the long-lived influence of this feature on inter- and intra-glacial sedimentology in the region. Complex glaciotectonism is observed across the dataset, including pervasive folding and a well-imaged landward-verging fold-and-thrust belt. Within this fold-and-thrust belt a mechanical stratigraphy results variable degrees of shortening and both brittle and ductile deformation. A terminal moraine is observed on both seismic reflection and high-resolution bathymetry data caused by seaward-verging ice flow.

The addition of the UHRSR dataset to the regional geoscience database enables ground models to be updated to reflect subsurface conditions more accurately. The interpretation of the UHRSR data has implications for subsurface fluid flow models and potential design considerations for the LLWR site in the Cumbrian coastal region. This highlights the value and importance of high-resolution datasets in improving our understanding of the subsurface and de-risking sites for the long-term disposal of nuclear waste.

Session Three: SITE EVOLUTION & ASSESSMENT STUDIES

New assessment workflow for borehole closure for the Final Ultra Deep Disposal (FUDD) concept in sedimentary formations

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TNO is investigating an initiative concept known as 'Final Ultra Deep Disposal' (FUDD) which involves a single large vertical borehole with a large diameter (approx. 1 meter), building upon previous work in the field of high-radioactive nuclear waste disposal. The investigation takes an integrated approach to explore both innovative drilling and borehole casing technology. The concept of ultra-deep boreholes for disposal benefits from a barrier which is several kilometers thick, enhancing the geological safety case while reducing costs compared to mining repositories. Another noteworthy aspect is the presence of specific sedimentary formations characterized by ductile and low permeability properties. These formations, by successfully hindering the migration of small hydrocarbon molecules over millions of years, demonstrate considerable promise for long-term benefits.
For the FUDD concept, a new drilling technology is employed for large diameter hole-making to accommodate present-day designed canisters without the need for repacking. To restore the formation to its initial non-permeable state for final closure, the casing is removed to avoid potential migration paths and to restore the creeping clay, salt, and sedimentary formations inside the borehole. A workflow is under development to evaluate all possible “self-healing” processes, such as creep of clay, and long-term natural fusion due to diagenesis and accelerated natural fusion methodologies within the borehole. Detailed data on the sedimentary formation and understanding of its properties, evolution and underlying mineralization processes are fundamental.

The FUDD concept that TNO is investigating involves a single large vertical borehole of at least 1 meter in diameter, which averts potential risky operations of repackaging nuclear fuel rods into different canisters tailored for more conventional sized borehole disposal. Present-day borehole casing technology is not designed to allow placement of currently used storage or disposal canisters at great depths. The borehole under consideration must be truly vertical with a smooth borehole surface to facilitate negligible risk of placement of the casing. A vertical borehole contributes to low-risk placement of radioactive material and reduces the likelihood of canisters getting stuck during insertion or removal. However, drilling a deep vertical borehole with such a large diameter and smooth surface presents a challenge with conventional mechanical drilling as it requires significant weight-on-bit and torque to generate the necessary forces for penetration and rock breaking. For the FUDD concept, Pulsed Power Drilling technology is considered the best solution for its distinguished "contactless" rock-cutting process, achieved through controlled high-voltage electric discharges that eliminate the need for mechanical force to break rocks. This characteristic is advantageous, as the borehole diameter is typically limited by the mechanical strength and power of existing drilling equipment. TNO is evaluating the FUDD concept for the sedimentary context such as in the Netherlands and other European countries which have substantial thick sedimentary formations with multiple non-permeable ductile formations. Restoring the same level of non-permeable properties in the borehole for final closure is an essential aspect of the proposed concept. The FUDD borehole concept design is aimed to be constructed with removable casing which allows self-healing ductile formations such as clay, shale, salt to creep in and “fuse” with re-installed captured borehole cuttings for final closure. The workflow for the assessment of final ultra-deep borehole closure is an integral part of the geological safety assessment of sedimentary formations reference (Altenburg et al., 2024) and the future geological evolution and effects on deep disposal of radwaste (Johan van Veen et.al., 2024). In this presentation, the workflow methodology will be outlined in the context of the concept of Final Ultra Deep Disposal in large-diameter boreholes within sedimentary formations

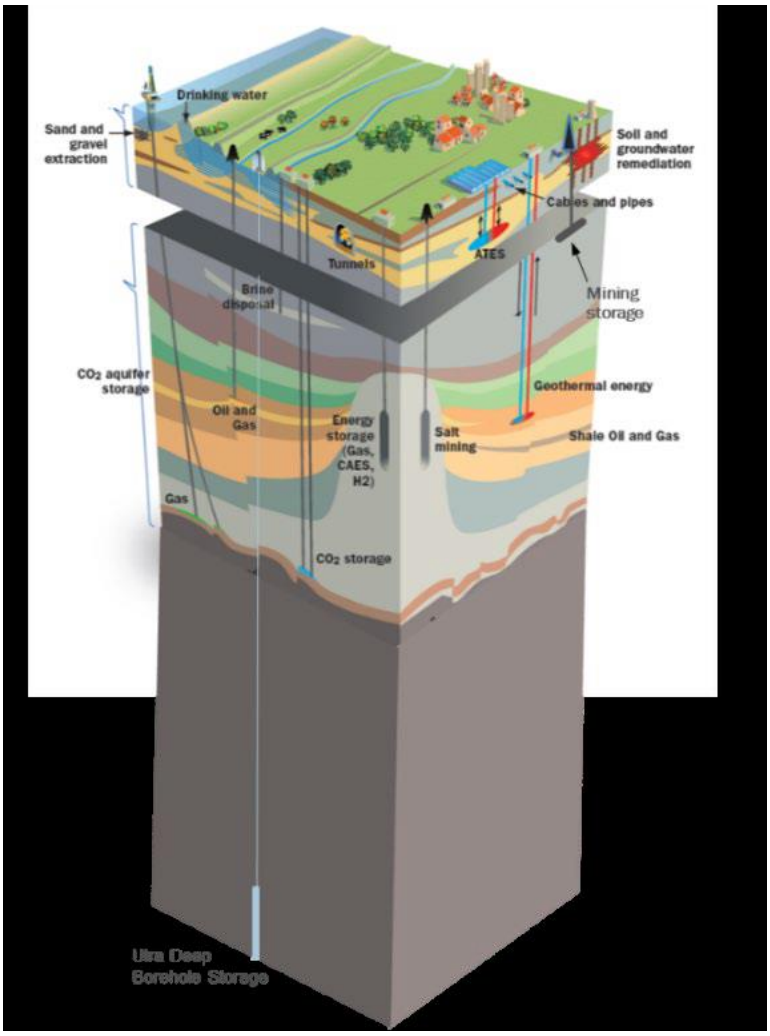

Figure 1- Typical activities in the subsurface, including the FUDD concept at 5km depth.

References

Altenburg et al. 2024. Final Ultra Deep Disposal: Geological Assessment of Borehole Storage in Sedimentary Basins, TNO

Ten Veen et.al. 2024. Future geological evolution and effects on deep disposal of radwaste in the Netherlands, TNO

Final Ultra Deep Disposal: Geological Assessment of Borehole Storage in Sedimentary Basin Settings

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With the ever-increasing demand for energy and the world focusing on low-carbon sources, it is evident that nuclear power will play a significant role in the foreseeable future. Nuclear power comes with nuclear waste which needs to be disposed. High-level radioactive waste (HLW) is currently stored in surface facilities, however, the long-term goal, is to isolate all forms of radioactive waste from the accessible biosphere. Several countries (e.g., Finland, USA, Sweden, France, and Switzerland) are making progress in planning and developing mined repositories for geological disposal of HLW. These developments concern near surface repositories (at 500 to 1000 meters depth). In this presentation another disposal technique is presented: Final Ultra Deep Disposal.

Final Ultra Deep Disposal (FUDD) is a proposed technological development for large-diameter deep borehole disposal of nuclear waste at depths of ~5000 meters. Such boreholes could make the deep disposal of radioactive waste safer, faster, cheaper, and potentially even more accepted by society compared to disposal in mined repositories which is currently the prevailing approach for disposal of HLW. With ultra-deep disposal, the waste is stored several times deeper than in the typical mined repositories. It relies on both the thickness of the overlying rocks as a safety barrier and on the isolating rock properties surrounding the waste as is the case in mined repositories. For example, at 5000 meters, it is well below the typical maximum depth of fresh groundwater resources and the disposal is isolated from the biosphere and any other surface process for a period extending into the far future.

Crystalline vs. sedimentary ultra-deep disposal

Currently, borehole storage has gained interest in several countries (e.g. United States Department of Energy and the Swedish Nuclear Fuel and Waste Management Company. At present, research into borehole disposal mainly focuses on metamorphic and magmatic rocks, whereas the potential of ultra-deep disposal in sedimentary basins is underexplored. A naturally occurring sedimentary formation can consist of several impermeable sealing layers, within a total thickness of up to 5000 meters, which holds promise in enhancing the geological safety case. Instead of one rock type, the barrier in this context would be multilayered and heterogeneous, with different compositions, including ductile shales, clay, salt, crystalline, and carbonate formations (Fig. 1).

This significantly improves the barrier system of the overburden which is known to comprise numerous effective seals for hydrocarbons with low permeability and porosity and which are effective already for millions of years. This inherent characteristic of the overburden is expected to prove advantageous as a future and long-term, reliable sealing barrier for disposal. This potential ultra-deep disposal in sedimentary basins is particularly significant in regions such as northwestern Europe, given that sedimentary basins form most of the subsurface.

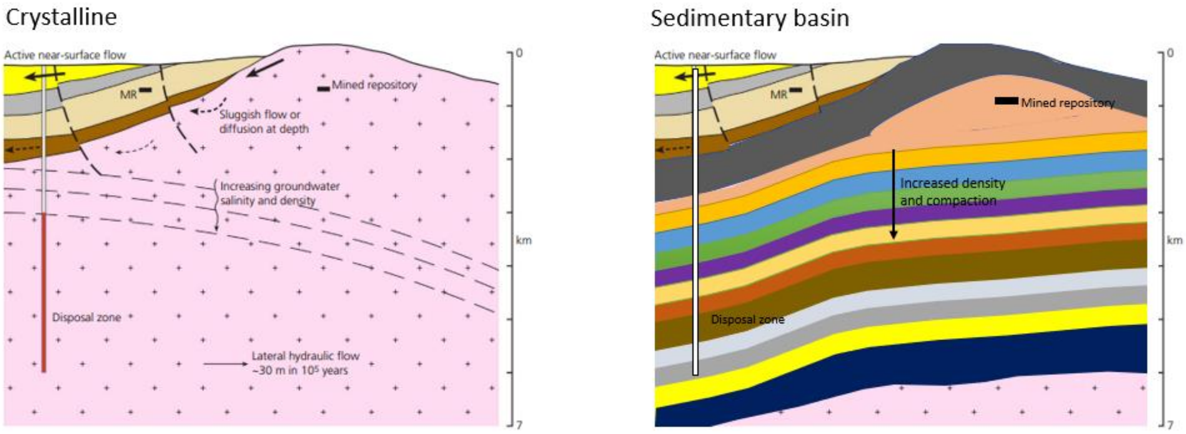

Figure. 1. Schematic of the ultra-deep borehole disposal in a crystalline setting and a sedimentary basin setting. Note the homogeneity in the crystalline setting and the heterogeneity in the sedimentary basin setting.

Geological assessment workflow

Whereas previous disposal studies focused on inventorying geoscientific factors that affect the performance of mined repositories, this study presents a systematic approach to evaluate geoscientific criteria for ultra-deep disposal in a sedimentary basin setting. To determine the geological safety case for ultra-deep disposal in a sedimentary basin setting, an assessment workflow will be developed to characterize the risks that are associated with ultra-deep disposal in sedimentary basin settings. This workflow will be based on a split-risking technique that has been used for decades in the hydrocarbon industry to de-risk prospects. By using such a workflow, different evaluation criteria are addressed. Evaluation criteria consider parameters that relate to the barrier function, mechanical stability, geological stability, and (sub)surface usage, which together make the ultra-deep disposal safety case. The parameters will be assessed and quantified based on static and dynamic geological conditions.

Future geological evolution and effects on deep disposal of radwaste in the Netherlands

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Radioactive substances and ionizing radiation find applications in various sectors such as medicine, industry, agriculture, research, education, and electricity production, resulting in the generation of radioactive waste. At present this waste is stored in surface facilities for a period that will last a minimum of 100 years. In the Netherlands, the ultimate goal is a long-lasting and safe solution to the disposal of radioactive waste. A globally recognized scientific and technical consensus supports geological disposal, involving the placement of radioactive waste in deep underground formations (the "geosphere") as the safest long-term disposal option. It ensures prolonged removal of radioactive waste from the biosphere and prevents future generations from exposure to radiation emitted by the waste. This presentation is centered around an assessment of how various processes influence the geological and geohydrological properties of the geosphere over a one-million-year timeframe. The focus is particularly on understanding how these factors may impact the long-term safety functions of conceptual radioactive waste disposal facilities in northwestern Europe, i.e. a region that is predominantly composed of sedimentary basins with thick and heterogeneous sediment accumulation.

Geological Disposal Facilities

As in many other countries, deep geological waste disposal is still in an early, conceptual phase. Over the past few decades much research has focused on the safety case of mined repositories in clay and rock salt. More recently, (see accompanying contributions of Heerens et al., 2024 and Altenburg et al., 2024), TNO is evaluating the Final Ultra Deep Disposal" (FUDD) concept that considers boreholes in substantially thick sedimentary formations with multiple non permeable ductile formations in the target 5 km depth range. Whereas in shallow mined and -borehole repositories the isolation safety function is primarily formed by the host rock and its geological coverage, the ultra-deep borehole disposal relies on a geological barrier that is several kilometers thick and heterogeneous. FUDD considers the restoration of the natural non permeable ductile properties of thick sedimentary formations due to creep in the borehole after removal of its casing as elementary aspect.

Geological evolution scenarios

In establishing a safety-case for the different types Geological Disposal Facilities (GDF's) an assessment is needed of geological and geomorphological boundary conditions that would influence the formation's mechanical and compositional integrity in the long-term (~1 Myr). This presented study is inherently multidisciplinary, and will offer an overview of well-documented (state-of-the-art) yet conceptual future geological scenarios (qualitative). Clear indications of potential ranges (semi-quantitative) are provided, serving as the foundation for defining boundary conditions in geo(hydrological) modeling exercises and test scenarios for radioactive waste disposal. Instead of delving into individual processes that are extensively covered in numerous studies over the past three decades, this study aims to address the intricate interplay of processes by outlining several potential future evolution scenarios (see Fig. 1). Each scenario includes indications of individual and/or combined effects. Central to this assessment is the question of whether these effects and processes are pertinent to the safety functions of various types of GDF's, including the deep borehole concept (FUDD). Three external driving forces encapsulate the primary processes influencing the future evolution of the geological and geohydrological properties of the geosphere: Climate, Geology, and Human actions (Fig.1). "Climate" involves processes resulting from anticipated changes in climatic conditions, while "Geology" primarily addresses processes related to (plate) tectonic. It is worth noting that certain processes and sub-processes may stem from more than one of these driving features (e.g., sea-level change). Additionally, processes triggered by one driving force may induce other processes (e.g., uplift or subsidence in relation to ice-sheet loading). At 5 km depth for disposal in deep boreholes, most of the future climate effects are irrelevant, which makes a strong case for the FUDD methodology. However, the evolution of depth-related temperature- and pressure effects on the time scale considered require special attention.

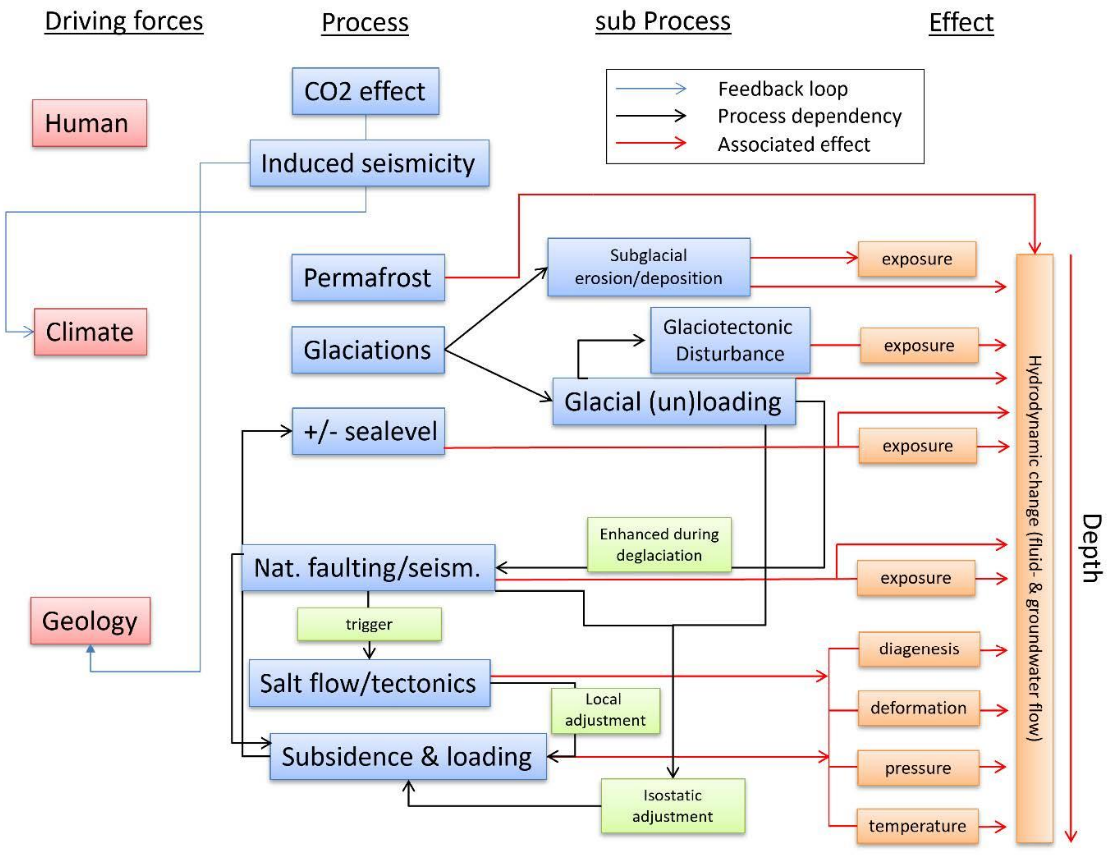

Figure 1 - Relationships between driving climatic, geological and human driving forces, (sub) processes and effects. Modified after Ten Veen et.al., 2015.

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Session Four: ANALOGUE STUDIES

The relevance of natural analogues to the German site selection procedure

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The German site selection procedure shall determine the national site for a deep geological repository for high-level radioactive waste with the highest possible safety for a period of 1 million years. The German Federal Company for Radioactive Waste Disposal (BGE) is responsible for the execution of this site selection procedure. According to the Repository Site Selection Act (StandAG, 2017), the procedure consists of three consecutive phases: Phase I starts with the definition of sub-areas, considering the entire German territory and three potential host rocks, i.e. rock salt, claystone and crystalline rock. The sub-areas defined during Step 1 of Phase I cover ~54% of Germany. The current Step 2 of Phase I narrows down these sub-areas to siting regions for further surface-based exploration during Phase II. The results of Phase II will determine potential sites for underground exploration during Phase III to finally select the most suitable site for the repository.

Preliminary safety assessments form an integral part of all three phases. These preliminary safety assessments increase in level of detail and complexity from representative (Phase 1) through further developed (Phase 2) to comprehensive (Phase 3). A central safety requirement is containment of the disposed waste over the entire assessment period of 1 million years within the so-called containment providing rock zone as essential barrier. However, for disposal systems in those crystalline host rocks for which a containment providing rock zone could not be defined, the German regulation also allows technical (= canisters) and geotechnical (= buffers) barriers to provide this long-term containment of disposed waste. The assessment of the region- and site-specific long-term evolution of the geological situation and the corresponding processes throughout the assessment period of 1 million years forms one cornerstone of the preliminary safety assessments.

To cover, predict and assess these long time scales and the corresponding processes within the preliminary safety assessments, studies on natural systems for e.g., scenarios, processes and system components form an integral part of the German site selection procedure. These so-called natural analogues offer the possibility to investigate the heterogeneity and complexity of natural systems over time scales and dimensions applicable to repository conditions but not assessable by experimental studies. Natural analogues are ideal to test experimentally derived models for long-term evolution in complex natural systems. Thus, natural analogue studies support the performance evaluation and long-term safety analysis for processes occurring in natural systems as well as the evaluation whether a considered aspect is relevant for the long-term safety or not.

The BGE therefore engages in various natural analogue projects to support the safety argumentation in the current and following preliminary safety assessments. The project CatchNet investigates the influence of hydrological and biochemical processes under (peri)glacial conditions on deep geological disposal. Within the 1 million years assessment period, the repository will be exposed to different climatic states. Scenarios indicate up to ten glacial and interglacial cycles affecting the repository's barrier. The project focuses on modelling, if necessary supported by experimental studies, based on natural analogue data derived from e.g., mapping of the periglacial landscape and the associated groundwater system. Similarly, the project “Search Depth” investigates the potential for subglacial erosion in the sub-areas identified in Step 1 of Phase I of the site selection process (Breuer et al., 2023). Using data from former glaciations, the potential range and depth of possible influences of future glaciations are predicted. The results are used to determine the sub-area-dependent repository depth level in order to keep the containment providing rock zone intact. Another important topic for the German site selection procedure is the long-term integrity of engineered barrier system and the materials used. As copper is part of many disposal container concepts, the long-term stability and processes occurring under natural repository conditions have to be investigated. The MICA project focuses on the in-situ stability of native copper from the Keweenaw Peninsula to investigate the long-term behaviour of copper and gain further insight into the stability of potential copper-based waste containers (Aaltonen et al., 2023).

Here, we present the contribution of studies on natural analogue systems to the German site selection procedure and show how natural analogue studies support the performance evaluation and long-term safety analysis for processes occurring in natural systems comparable to potential repository sites.

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International Bentonite Longevity (IBL) project: an overview

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Kunimine Industries' Tsukinuno deep bentonite mine in NW Japan is a source of Miocene age (5.3 – 23.0 Ma) Na- bentonite (with Ca-bentonite near surface) and the site is ideal 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, including tunnel and borehole seals.

In the Tsukinuno area, some 31 bentonite layers vary in thickness from a few cm to ca. 7 m, providing information of relevance to the scales of the repository buffer, backfill and tunnel and borehole seals. In addition, bentonite compositions vary, providing the potential for studying processes in relation to various initial states of the buffer/backfill/seals. The bentonite also occurs across a range of depths (currently accessible down to 300 m below surface) 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.

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

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

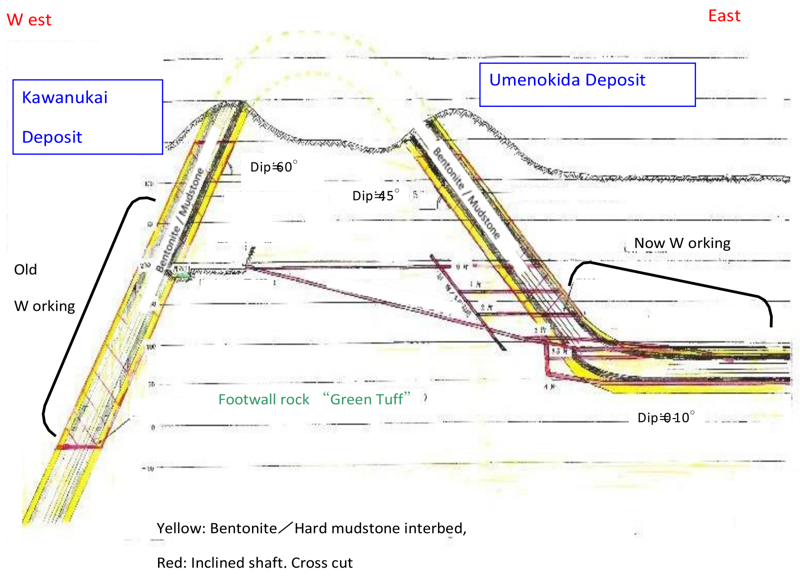

Figure 1: cross-section of the Tsukinuno bentonite mine showing the working drifts and main bentonite deposits (image courtesy Kunimine Industries)

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

Saturation state – natural saturation states of bentonite in differing environments (on the surface and at varying depths underground, under dry and wet host rock conditions) for comparison with current SC assumptions (based on short-term, laboratory and underground rock laboratory 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 both surface and deep groundwater chemistries, including changes in cation exchange capacity and exchangeable cation composition across thin and thick bentonite beds (representing a range of bentonite uses from canister buffer materials to borehole seals to tunnel seals)

Microbial activity – microbial populations in natural bentonites as analogues of similar populations in the repository engineered barrier systems

Bentonite response to fracturing/faulting – assessment of the true impact on bentonite properties when a fracture propagates/fault movement occurs from the surrounding host rock into/through the bentonite

Long-term bentonite durability – following reaction with mudstone and siltstone host rocks over millions of years

Bentonite erosion – both under repository-relevant conditions at depth in the tunnels where water conducting features contact the bentonite and under extreme conditions such as erosion from surface-water processes

Stakeholder communications – use of 'real' examples to explain repository safety concepts to a wide range of stakeholders

Bentonite sampling and analytical development – novel sampling, transport, storage and analytical approaches are being explored as an integral part of the project

The results of the project to date have been presented in Reijonen & Alexander 2024 (please see www.iblproject.com for further information on this and other IBL reports). Here, an overview of the existing results and ongoing project work will be presented along with a discussion of the SC relevance (including verification/validation of numerical models of long-term bentonite behaviour, e.g. saturation processes) of the project output.

Figure 2: sampling at surface outcrops
(image W.R.Alexander)

Figure 3: drilling in the mine tunnels
(image H.M.Reijonen)

The engineering properties of low strength sedimentary rocks – Evidence from the construction of the High Speed Two railway

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The engineering properties of low-strength, sedimentary rocks can vary from those of rocks to those of soils. This behaviour is well-known for stiff clays and weathered mudstones, but it can be difficult to obtain sufficient data to establish baseline properties for a particular outcrop or location. This increases uncertainty during the design and construction of engineering structures (e.g. excavations, tunnels) that can result in over-conservative design or result in delays and adjustments during the construction process – both of which lead to financial or reputational losses for large infrastructure projects.

The construction of the High Speed Two (HS2) railway in central England has generated large ground investigation datasets from which to establish baseline engineering properties for a range of Jurassic and Triassic-aged mudstone strata (e.g. from the Lias Group and Mercia Mudstone Group). This paper describes the interpretation of ground investigation data from 373 individual exploratory boreholes within the Charmouth Mudstone Formation (Lias Group) across an 18.2 km length in central England. The ground investigation included in-situ and laboratory tests to characterise the strength and stiffness of the clays and mudstones at various states of weathering. The boreholes were logged using visual weathering classifications (Classes A-E) for soils and weak rocks, ranging from unweathered mudstone (Class A) to reworked clay (Class E).

The results from the ground investigation show that the engineering properties of the Charmouth Mudstone Formation, and other ‘old’ mudstones, can vary from low-strength, ductile, clay-like materials to high-strength, brittle, rock-like materials. Clay-like properties were measured for stiff clay and mudstone that had been disturbed and remoulded, whether in-situ (due to glacial and periglacial weathering) or reconstituted in the laboratory. Rock-like properties were measured for undisturbed, intact material located at depth within the weathering profile. For example, stiff clay and weathered mudstone (Class Bb-E) was described in borehole logs as grey or brown, closely fissured clay and showed low shear strength (<300 kPa) that could be correlated with the sample moisture content (Figure 1). Unweathered material (Class A) was described in borehole logs as grey mudstone with a higher strength that could not be correlated to sample moisture content. However, the results showed that it is difficult to identify and classify the partially weathered mudstone that lies between these two states. This (Class Ba) material has the visual appearance and index properties (e.g. colour and moisture content) of high-strength, unweathered mudstone. However, in most cases it has the low strength of a clay (i.e. <300 kPa). A similar, gradational transition from soil-like to rock-like characteristics was shown in the ground stiffness profile obtained from in-situ shear-wave velocity measurements (Figure 2) and complementary bender-element tests on laboratory samples.

The investigations show the relative utility of borehole log descriptions, in-situ tests and laboratory tests to measure the strength and stiffness of stiff clays and weak rocks. These can be used to inform an appropriate ground model for mudstone strata subject to weathering or other disturbance (e.g. construction activities). They also provide baseline information about the characteristics (e.g. structure, weathering profile) and engineering properties of the Charmouth Mudstone Formation and other similarly-aged mudstone strata.

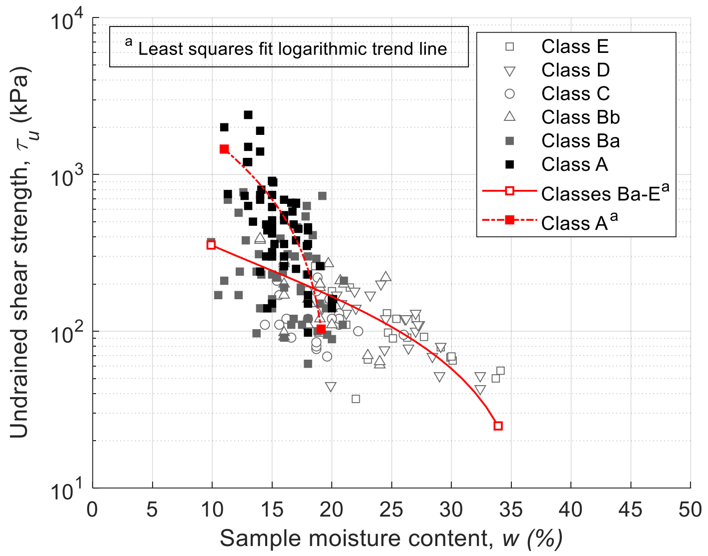

Figure 1: Undrained shear strength compared to sample moisture content for 223 unconsolidated undrained (UU) triaxial tests on weathered (Class Ba-E) and unweathered (Class A) samples from the Charmouth Mudstone Formation.

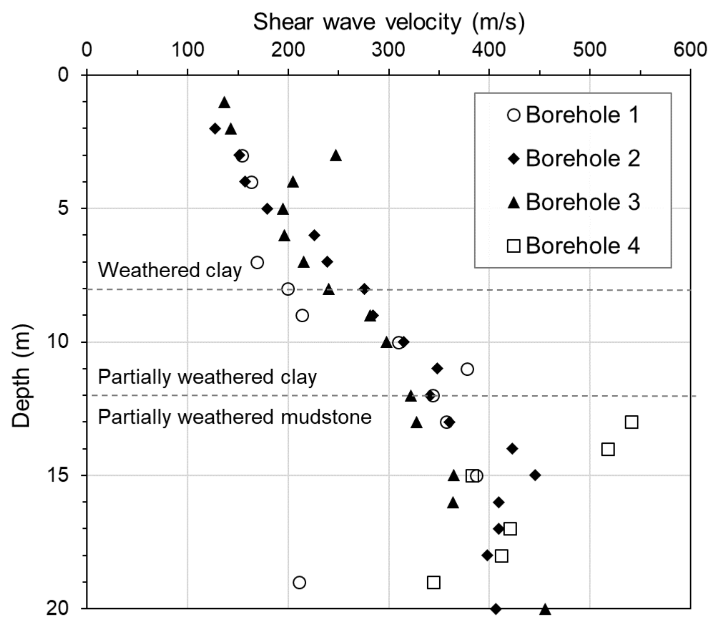

Figure 2: Shear wave velocities measured in downhole geophysical tests at four adjacent borehole locations in the Charmouth Mudstone Formation in Oxfordshire, England.

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Multiscale-multiproxy seal assessments of Mesozoic mudrock units in North Yorkshire, a potential aid to screening and modelling radioactive waste disposal facilities

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Lower strength sedimentary rocks, namely low-permeability, fine grained sedimentary successions or mudrocks, have been identified as prime lithologies for geological disposal facilities (GDFs) in the UK (Turner *et al.*, 2023). Triassic to Early Jurassic mudrock and mudrock-halite units comprise approximately 10% of the UK's onshore outcrop and subcrop by area (~26,000 km^2; Fig 1i). A considerable volume of these rocks are sited within the 200–1000 m subsurface realm appropriate for GDFs.

CASP's research programme in the Cleveland Basin, North Yorkshire has sampled and logged more than 600 m of continuous stratigraphy. The studies have targeted both outcrop and shallow borehole core to examine the impacts of heterogeneity in mudrock units on seal potential for geological carbon sequestration (GCS). The studied successions include the lower Lias Group in outcrop, primarily at Robin Hood's Bay, as well as the entire Mercia Mudstone and lower Lias groups in a nearby onshore core (Fig. 1ii & iii). Here, the results of the initial phase of this investigation, addressing ~180 m of the lower Lias Group in outcrop, are presented (Fig. 1A).

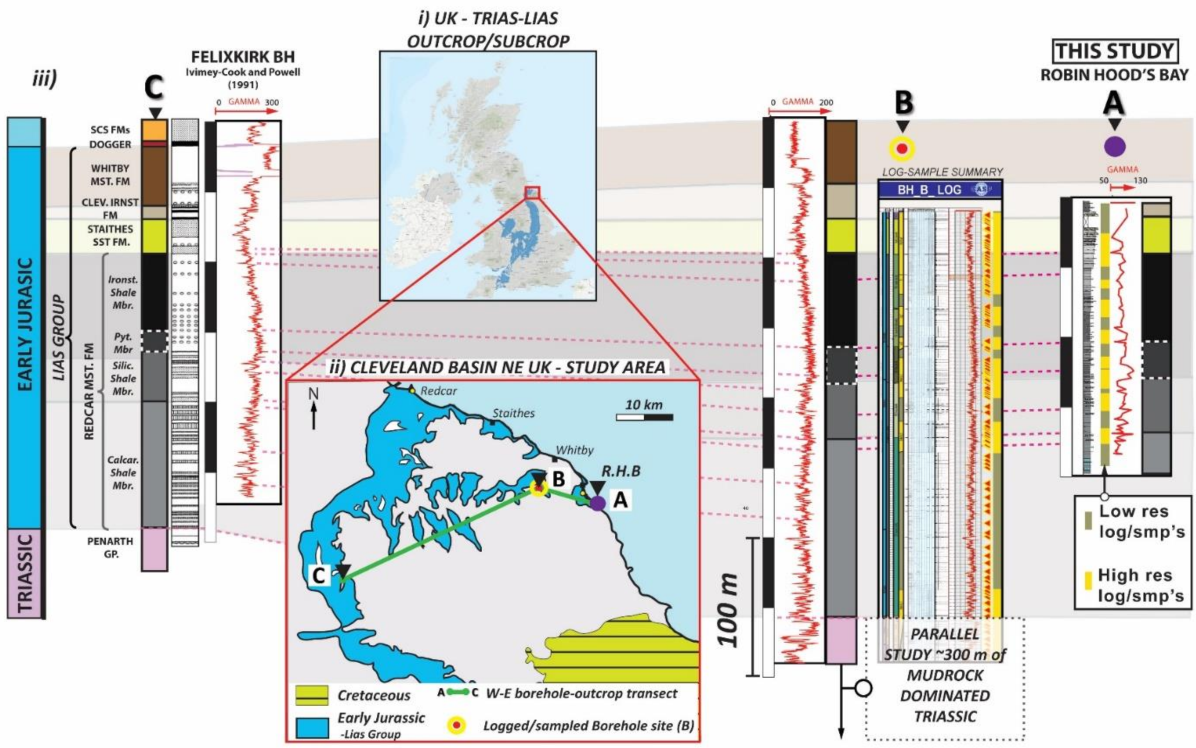

Fig 1. i) Location map showing study area (red box) and extent of Early Jurassic–Triassic mudrock subcrop in UK (in blue) (with considerably more in near offshore realm). ii) The Cleveland Basin study area, (A) outcrop study interval and linkage to key subsurface data, and iii) an accompanying fence diagram (A-C) illustrating the outcrop and adjacent subsurface dataset context along a W-E transect.

The aim of the outcrop investigation is to link a comprehensive catalogue of primary (compositional and sedimentological) and secondary (deformation-related) heterogeneities to variations in seal integrity and potential. To capture compositional variability, we combined sedimentary logging (1:200; 1:25) and facies analysis, hand-held gamma/X-ray fluorescence (XRF) analysis, quantitative X-ray diffraction (QXRD) analysis, optical petrography (microfacies analysis) and scanning electron microscope energy dispersive spectroscopy (SEM-EDS). Mechanical stratigraphy is examined via field measurements and lab analyses. Targeted porosity-permeability and mercury injection capillary pressure (MICP) analyses underpin assessments of seal potential.

Following compositional analyses, the sediments are identified as dominantly siliceous shales, and classified into groupings/subgroupings based on mineral content. Broadly speaking, compositional heterogeneity is secondary to textural heterogeneity; the latter is strongly modulated by the shallow marine depositional mode and setting. The initial poro-perm assessments largely track this primary trend, modified by pervasive bioturbation. As suggested by previous studies (e.g. Hobbs *et al*., 2012), the compositional and clay-type signatures contrast with those of the Lias Group of southern England, but provide a closer analogue to deeper units prospective for GDF development in Lincolnshire. Mechanical stratigraphy confirms increased fracture density towards fault damage zones and suggests that only a small (mineralised) subset of surficial fracture networks are likely to be an issue at GCS depths (>1800 m); however, their relationship with shallower GDF target depths is less clear. Initial bed-by-bed correlation to local subsurface data ~6 km from the outcrop investigations reveals a largely layer-cake stratigraphy and close alignment in gamma/XRF signatures. The results are encouraging with respect to the seal potential of the succession.

The results of this study, alongside the adjacent subsurface dataset produced by the wider research programme, can be employed to inform desk-based GDF site screening. Where appropriate, our data may also feed into multiscale site geomodels evaluating geomechanical or reactions-based behaviour, which will be key to demonstrating site safety. Additionally, this dataset can help to understand data gaps associated with borehole-only appraisals.

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Contribution of programming language to novel mine risk assessment project Abstract

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When excavating a tunnel, the stresses are distributed asymmetrically along the tunnel cross-section. Other factors, particularly slope friction force and excavation speed, can also contribute to the deformation and displacement of a tunnel. Despite this, several authors have used the complex potential method to predict the ground deformation surrounding the tunnel. However, their applicability to the ground response caused by the asymmetric stress distribution around the mine wall is analyzed in this context. This project, therefore, proposes an approximate solution on the slope to predict the mine cross-section deformation. The solution is based on the complex potential method to predict analytically and numerically the ground deformation around the tunnel. However, two variables called the “complex potential functions” for the Laurent series expansion are used for the stress redistribution to the tunnel boundary conditions. Data from the Datong mine case are used to justify the proposed analytical solutions. The solution is an essential guide for analyzing deformations in complex geological conditions and structures, such as steeper slopes.

New insights into the Muhos Formation, an unmetamorphosed Mesoproterozoic sedimentary rock sequence in central Finland

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The Muhos Formation, located in central Finland (Fig.1), is an exceptionally well-preserved sedimentary rock sequence occurring along the northeastern coast of the Gulf of Bothnia, with significant extensions offshore. This poorly exposed formation has been investigated by extensive drilling programmes over the past decades and the overall stratigraphy has been described in the literature. In recent years, the Muhos Formation has again received increasing attention due to its unusual lithological properties when compared to the typical Finnish crystalline bedrock, including studies of hydrogeochemical-microbiological processes and geothermal properties in mudrocks.

Accordingly, the TUPOS-001 core (Fig. 2) was selected for the hyperspectral imaging program of the Geological Survey of Finland, conducted in the context of a larger National Digital Drill Core Archive (NDCAF) project. In that project, over 1 km of drill core was scanned in 2021 using the Specim SisuRock imaging system which acquired data in the visible-near-infrared (VNIR), short-wave infrared (SWIR) and long-wave infrared (LWIR) wavelength regions. These imaging data were complemented by point spectral measurements acquired in the VNIR-SWIR-LWIR and mid-wave infrared (MWIR) wavelength regions. To calibrate and validate the hyperspectral dataset, extensive sampling was undertaken for petrography and automated SEM-EDS mineral analysis.

Here, we present the first results of the new analytical data sets and an overview of the validated hyperspectral analysis results. The presentation aims to showcase the workflow and provide a future outlook for research opportunities. Specific emphasis is placed on assessing the significance of the lessons learned regarding site assessments of similar geological units, such as the Mercia Mudstone Group in England.

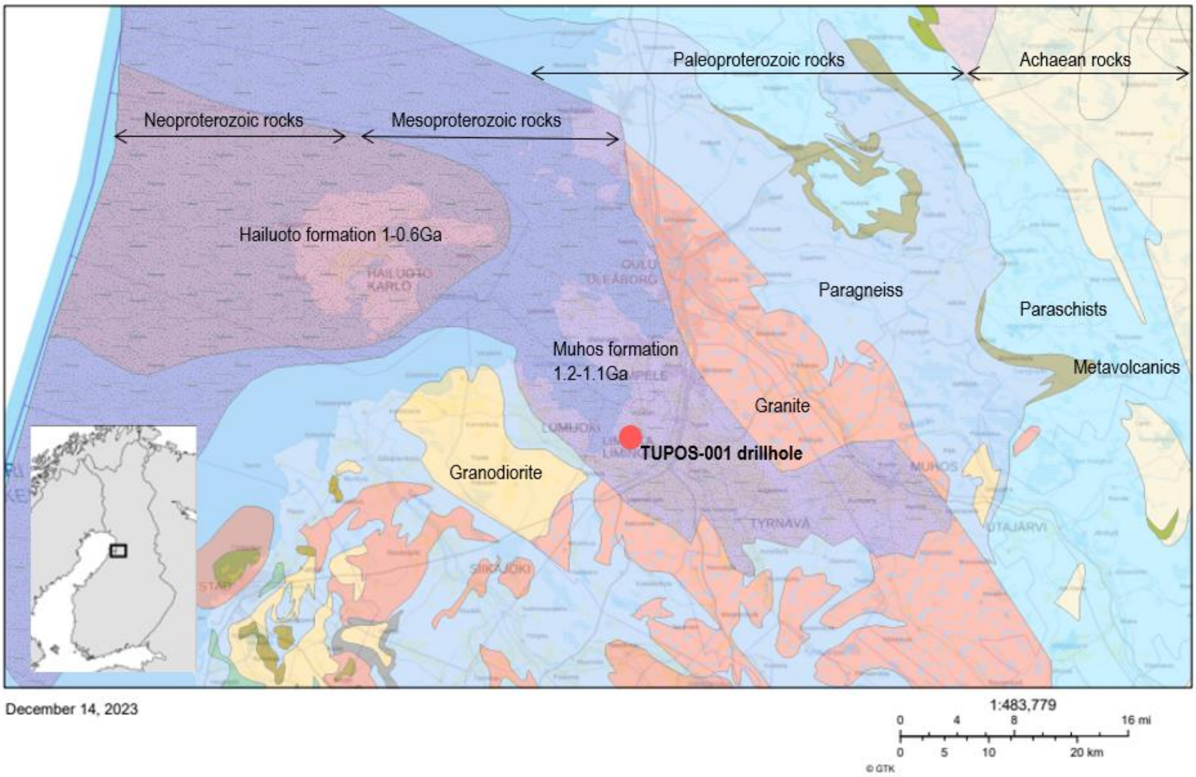

Fig.1. A simplified geological setting of the Muhos formation and the location of the drill hole TUPOS-001.

Fig. 2. The TUPOS-001 drill core laid out for inspection (Image H.M. Reijonen).

Progress point on the Cigéo Project, the French geological disposal project for the most radioactive waste

Frédéric PLAS, Andra (French national agency for radioactive waste management), Cigéo Programme Director

On January 16, 2023, Andra submitted the licensing application (DAC) for Cigéo, the French geological disposal project for the most radioactive waste. This pivotal stage marks both an outcome and a new beginning for the project. It is the result of 30 years of a progressive development, regularly reviewed. The Cigéo project has been progressively designed over time (feasibility principle, sketch, basic design, detailed design) on a scientific and technical level, to submit a DAC based on well-defined design principles and a robust safety demonstration. This submission and its instruction by the French Nuclear Safety Authority (ASN) also reflect the beginning of a new phase: Cigéo is preparing for its initial construction and Andra becomes its operator, already responsible to the ASN. This also involves progressing gradually during this instruction, first specifying certain elements to prepare for the initial construction and then the operation. Cigéo is also the convergence of a national project, supported by the French state, and a host territory, the Meuse and Haute-Marne departments. Continuing to involve local stakeholders in future choices and decisions is the guarantee of lasting confidence.

The DAC presents a reference radwaste inventory (based in particular on reprocessing of all spent fuel) to support repository design et safety demonstration (operation and post closure long-term) and adaptability studies based on a reserve inventory to demonstrate that Cigéo will be able to adapt to changes in radwaste inventory due to changes in French energy policy (such as stop of spent fuel reprocessing) or uncertainties regarding management of some radioactive waste (such as some graphite). The DAC aims to obtain the creation authorization decree. Furthermore, after construction and tests, a commissioning authorization by ASN will then be necessary to operate and dispose first radwaste disposal packages. In that context, the reference inventory does not prejudge the inventory which will be authorized with the creation authorization decree.

Cigéo will have a progressive deployment over one century, starting by an industrial pilot phase. If the creation of Cigéo is authorized, the initial construction phase will begin, that is to say the period during which the surface buildings and underground structures are built to receive and emplace the first radwaste disposal packages. This set of buildings and structures is called “Tranche 1”. Underground works dedicated to technological demonstrations will be also built. These “demonstrators” will not receive radwaste packages and will not participate in the long-term containment of radionuclides. It is during this initial construction phase that operational testing of Cigéo will begin. The disposal and, as part of the reversibility requirement, withdrawal operations will first be tested using radwaste disposal package models. Conventionally, radioactive sources will be used to verify the performance of radiation protection equipment. After the commissioning authorization, the operating phase of Cigéo will begin, with active start-up tests with radioactive waste packages, then industrial disposal operations will be implemented. As provided for by the French 2016 law specifying the terms and conditions for creating a reversible disposal facility in a deep geological layer for High level long-lived and intermediate level long-lived radioactive waste, the pilot industrial phase will be the subject of a report from Andra that will be reviewed for a decision-making process resulting in a law which will define the conditions for the continuation of the project.

Session Five: GEOMECHANICAL STUDIES

Some geotechnical considerations for nuclear waste disposal in the Mercia Mudstone Group

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The Mercia Mudstone Group occurs widely across the UK and within the engineering vicinity of existing community partnerships. Deposits are often several hundred metres thick and can extend laterally over vast areas at depths up to 2500m. This makes it an attractive host rock for a geological disposal facility (GDF). Recently, an engineering study on an unprecedented scale has been undertaken on this geology for High Speed 2 (HS2) offering a wealth of ground investigation data and importantly, ground response data through construction.

To facilitate the civil engineering design of an underground storage facility and its ancillary infrastructure, in-situ geo-mechanical properties such as mass strength and stiffness must be characterised from ground surface to disposal depth. Most commonly, ground information for engineering projects in the UK is gathered from near surface geotechnical investigations. Therefore, a wealth of historical geotechnical data exists over depths much less than 100m. Petrophysical data to depths of several kilometres, a legacy of oil and gas exploration, provides some properties within the accuracies required for civil engineering design, but are less abundant. There lies an opportunity within our ability to accurately corelate these shallow geotechnical and deep petrophysical datasets.

On behalf of Nuclear Waste Services, Mott MacDonald completed a national study of the properties of the Mercia Mudstone Group which used:

- Shallow (<100m) ground data from HS2 Phase 1 and BGS' National Geotechnical Properties Database; and
- Deep (100-2000m) petrophysical data.

The shallow data set contained some 30,000 records from laboratory classification testing on Mercia samples, which consistently indicated that index properties change most rapidly within the first 100m, where the effects of weathering and stress relief are greatest. Deep petrophysical data suggested that index properties vary gradually and predictably beyond 100m. Good agreement between density measured in laboratories and by in-situ petrophysical methods was found and a continuous profile of density could be predicted for the Mercia from surface to 2300m.

Correlation of key engineering properties with this abundant density data was explored to address the shortage of engineering data at depth. Log-linear correlations between Unconfined Compressive Strength (UCS) and bulk density were identified from shallow geotechnical testing, which were used to extrapolate UCS to disposal depths. A small number of UCS results from depths of up to 600m complement this correlation. Validation from a larger number of deep UCS testing is required.

As well as extrapolation from shallow to deep environments, how reliably can we extrapolate data from basin to basin? The national data on the Mercia Mudstone Group suggests that lateral variability does not appear to be severe and that a similar range of geotechnical properties may be expected from one basin to another. This is advantageous, for example when comparing well-established properties from onshore investigations to those interpreted from the overwater investigations likely to be necessary for the UK GDF.

A GDF and its ancillary structures in the Mercia Mudstone Group must consider several time-dependent geological mechanisms over its construction, operational and post-closure phases.

The Mercia possesses sulphates (anhydrite/gypsum) and soluble evaporites (halite), which have historically caused significant engineering challenges. Examples of extreme tunnel deformations due to volumetric expansion of the ground by sulphate mineralisation are known in similar geologies. Control measures to prevent anhydrite remineralising as gypsum, with associated volume increase, are most effectively made during the construction and operational phases.

Surface subsidence due to collapse of underground voids formed by halite dissolution at depths of naturally circulating groundwater is well known in the UK. While, naturally circulating groundwaters are not anticipated at disposal depth, the GDF structures could introduce groundwater mobility if the tunnel openings were to drain the ground, or by thermal convection associated with the emplacement of exothermic radioactive waste.

Smectite is a clay mineral that occurs in varying quantities throughout the Mercia between formations and even from bed to bed. It’s capable of causing volumetric expansion or contraction depending on the ambient water availability and stress conditions. Associated swelling strain or stress magnitudes are often easily accommodated within normal engineering design. Unlike most civil infrastructure tunnels, the GDF will impose a localised temperature increase potentially driving water from the in-situ clays then recover slowly as the heat dissipates and as the waste decays.

All host geologies offer their own engineering challenges, and the Mercia Mudstone Group is no exception, but experience from deep tunnels in European Triassic mudstones and the current focus on MMG in the UK have made its engineering properties and challenges relatively well-known.

Assessing the Fracturing Mechanisms and Evolution of the Excavation Damage Zone of Underground Structures in Hard Rockmasses for Disposing Nuclear Waste

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Underground containment facilities for nuclear disposal and management are required to be designed and constructed so that the biosphere and ground surface will remain stable and minimally affected due to short and long-term geological considerations and processes with a view to containing the hazardous materials. It is well known that the excavation induced damage on the surrounding ground of an underground opening results in its fracturing, hence increasing the permeability from the undamaged material. This zone of increased permeability can be a potential leakage pathway or contaminant transport. Therefore, an accurate and rigorous assessment of the depth and shape of the excavation induced damage is required.

Determining the depth of damage in underground excavations is a significant requirement for the design process, especially for permeability sensitive underground openings such as the geological disposal facilities (GDFs) for nuclear waste storage, as radionuclide need to be prevented from escaping the geological barrier used for isolation through the excavation damage zone (EDZ). The damaged zones, while collectively being usually referred to as the excavation damage zones (EDZs), can be grouped into different categories depending on how the damaged is induced and how it changes the permeability of the surrounding ground around an opening (Figure 1).

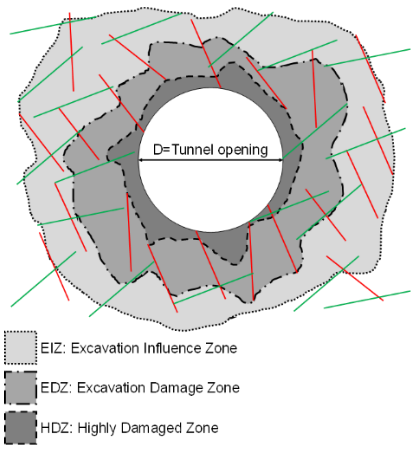

Figure 1. The excavation damage zones (EIZ, EDZ, HDZ) and the effect of rockmass structure (red and green lines) on the damage profiles.

To understand the mechanisms behind the excavation induced damage in underground excavations, we have conducted research by using the finite-discrete element method (FDEM). Numerical models were examined under various conditions in order to investigate the effect of key factors affecting the rockmass behaviour during an underground excavation, including the discontinuity geometry pattern by using Discrete Fracture Networks (DFNs), discontinuity strength, and the magnitude of the initial in situ stresses, along with the associated excavation induced damage and its evolution (Figure 2).

Obtained numerical results (Figure 3) demonstrated the significant role of the joint geometry pattern in the manifested excavation induced damage, the impact of pre-existing joints on stress localization and dissipation, as well as their ability to re-direct and contain the damage within a specific region. Increased fracture intensity (total length of discontinuity traces within a mapped area) under a constant persistence condition led to a greater rockmass strength and extensile potential reductions, as well as greater stress induced damage extents.

However, by varying the persistence under a constant fracture intensity value provided a variation of results that revealed the importance of the position of the discontinuities relative to the excavation boundary and their overall spatial distribution. Moreover, from the conducted analyses for different joint strength parameters it was inferred that the role of the discontinuity geometry pattern and discontinuity spatial distribution are more critical in non-persistent discontinuous systems than the applied discontinuity strength, unless really high strength parameter values were used. Additionally, by using this approach, the in situ stress-discontinuity network geometry interaction showed that specific stress localization and stress relief conditions because of a particular joint pattern may lead to extensive collapses even at lower value mean stresses, as result of the extreme changes in geometry caused by the excavation induced damage around the underground opening.

The state-of-the-art numerical modelling has been paramount to provide a better understanding of the critical role which pre-existing discontinuities play during the excavation of an underground opening in terms of the stress-induced damage, critical to the GDF development. Furthermore, the complex interactions between damage induced cracks and the rock mass discontinuity pattern have been captured in the numerical models to provide useful insights of the interconnectivity between excavation induced and natural fractures to assess the extent of the EDZ and its significance in the operational life of a GDF and steer in a specific direction the application of potential mitigation measures.

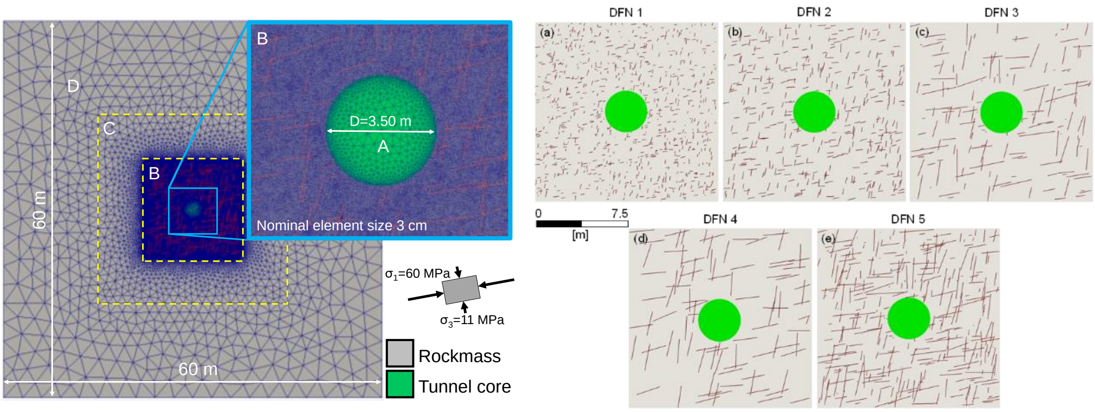

Figure 2. (Left) Tunnel model configuration (geometry and applied stresses) and (Right) Different discontinuity patterns adopted in the analysis.

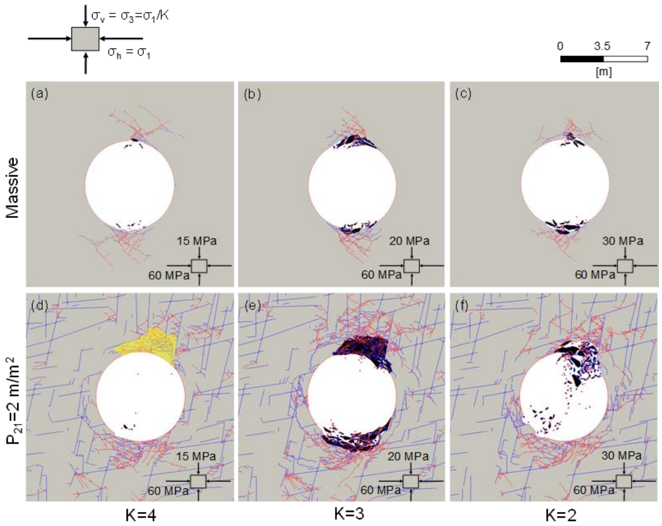

Figure 3. Impact of the discontinuity pattern and in situ stresses on the fracturing mechanisms and development of the EDZ.

Modelling of Spalling around Deposition Boreholes in a

Geological Disposal Facility for Nuclear Waste

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The Rock Mechanics Research Group at Imperial College, in collaboration with the Swedish Nuclear Fuel and Waste Management Company (SKB), have conducted extensive three-dimensional numerical simulations of the development of an excavation damaged zone (EDZ) around deposition boreholes in an underground GDF. The development of the damage zone was simulated with the Imperial College Geomechanics Toolkit, a finite-element based simulator that can model the simultaneous nucleation, growth, and coalescence of multiple fractures in quasi-brittle rock. The simulations have utilised rock mechanical properties and *in situ* stresses that were measured/estimated at the Swedish Forsmark site.

Firstly, the development of a damage zone due to the mechanical stress concentrations around the boreholes was modelled as a function of the *in situ* stress state, tunnel orientation, borehole geometry, total number of boreholes, and borehole spacing. Numerical results show that, given the underground conditions at Forsmark, spalling will occur in all cases, with borehole geometry, spacing, and stresses affecting the extent of fracture nucleation and growth patterns. The influence of uncertainty in underground stress conditions was evaluated by varying the stress magnitudes and orientations relative to the tunnel floor. Massive failure is predicted to occur if the inter-borehole distance is small enough that adjacent ‘‘spalled’’ regions interact; specifically, through-going fractures will develop when the centre-to-centre borehole spacing is less than about 4 m.

Next, the effect of the thermal stresses that are caused by the radioactive decay of the waste was simulated. In these simulations, the boreholes are heated by imposing a heat flux at their walls, which varies in time following the power-decay characteristics of a typical spent fuel canister. The simulations indicate that thermal stresses will increase the depths (away from the borehole) and angular widths of the spalled zones, but are not likely to lead to major increases in fracture aperture, or concomitant increases in hydraulic transmissivity and permeability of the spalled zone, above that which has already been caused by mechanical spalling.

Lastly, the effect of the changes in *in situ* stresses due to glaciation cycles was investigated. After the thermo-mechanical phase is completed, the model was subjected to the far-field stress path that is expected to occur at Forsmark during the next glaciation cycle. Fracture patterns and damage zones were compared after the borehole drilling, heating, and glacial loading stages. The simulation results showed that glaciation-induced stress changes will influence the reactivation of pre-existing spalling fractures, and increase the extent of the spalled rock around the deposition boreholes during the glacial maxima.

A similar investigation of the spalling damage that may occur in a GDF located in lower-strength sedimentary rock (LSSR) in the UK is planned to be conducted, commencing in late 2024, within the GeoSafe project, a multi-university project that is jointly funded by the Natural Environment Research Council and Nuclear Waste Services. These simulations will utilise rock thermo-mechanical properties of a range of LSSR rocks that are thought to be representative of possible repository host rock locations in the UK.

Modelling Techniques for Simulating the Excavation Damage Zone around Deep Underground Excavations

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The nature and extent of the Excavation Disturbance Zones (EDZ) is an important element to characterize for the design of underground excavations, such as the response of the rock mass adjacent a Geological Disposal Facility (GDF). In this paper the available tools and theoretical background for simulating the Excavation Damage Zone (EDZ) around underground excavations is presented. Special attention is given to the selection of appropriate constitutive relationships and modelling techniques for the analysis including continuum and discontinuum approaches. A series of continuum and discontinuum models were run using the Universal Distinct Element Code (UDEC) for a circular excavation at a prescribed depth. For the discontinuum models, a FracMan Discrete Fracture Network (DFN) was embedded into the rock matrix to represent a massive to moderately jointed rock mass. Block strength was shown to be an important factor in discontinuum modelling. As block strength reduces then the extent of damage and rock mass deformation increase; therefore, careful block characterisation is needed to avoid the underestimation of rock mass strength. When blocks are simulated as continuum material in between the joints, the traditional Hoek–Brown approach overestimates the in-situ strength of blocks and thus the disturbed zone and magnitude of displacements are underestimated. While the application of a modified Damage-Initiation and Spalling-Limit approach captures the expected low confinement zone near the excavation boundaries due to extensional fracturing. When blocks are simulated as a packing of Voronoi elements, it is shown that significant effort is required to calibrate the Voronoi micro-properties for tunnel-scale problems. The results show that the Voronoi models predicted a considerably reduced damage, stress relaxation and deformation when combined with the pre-existing discontinuities. The Voronoi skeleton is believed to provide a more realistic rock mass behaviour by creating a well-interlocked structure that clamps the pre-existing joints, allowing in this way the stress-induced slabbing type of failure to dominate the behaviour of the model before the activation of any kinematic instabilities. The work highlights that the estimation of representative block properties is of equivalent importance with the selection of appropriate modelling approaches and constitutive relationships.

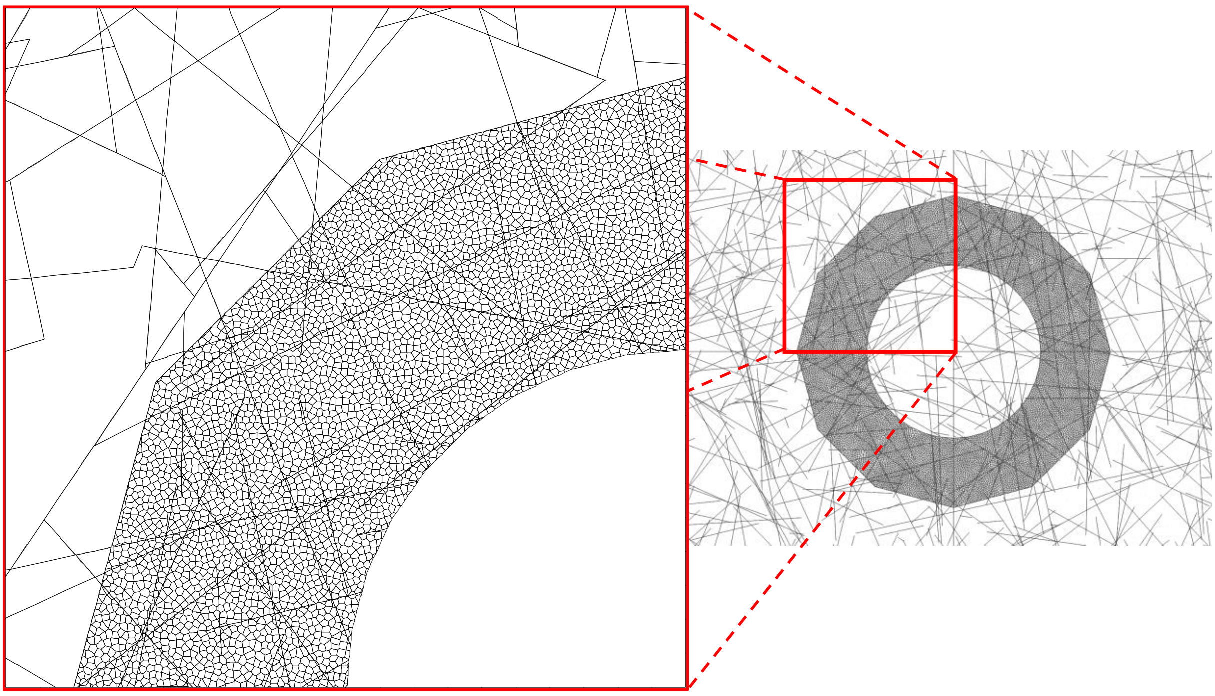

Figure 1: Synthetic Rock Mass geometry developed in UDEC with FracMan DFNs

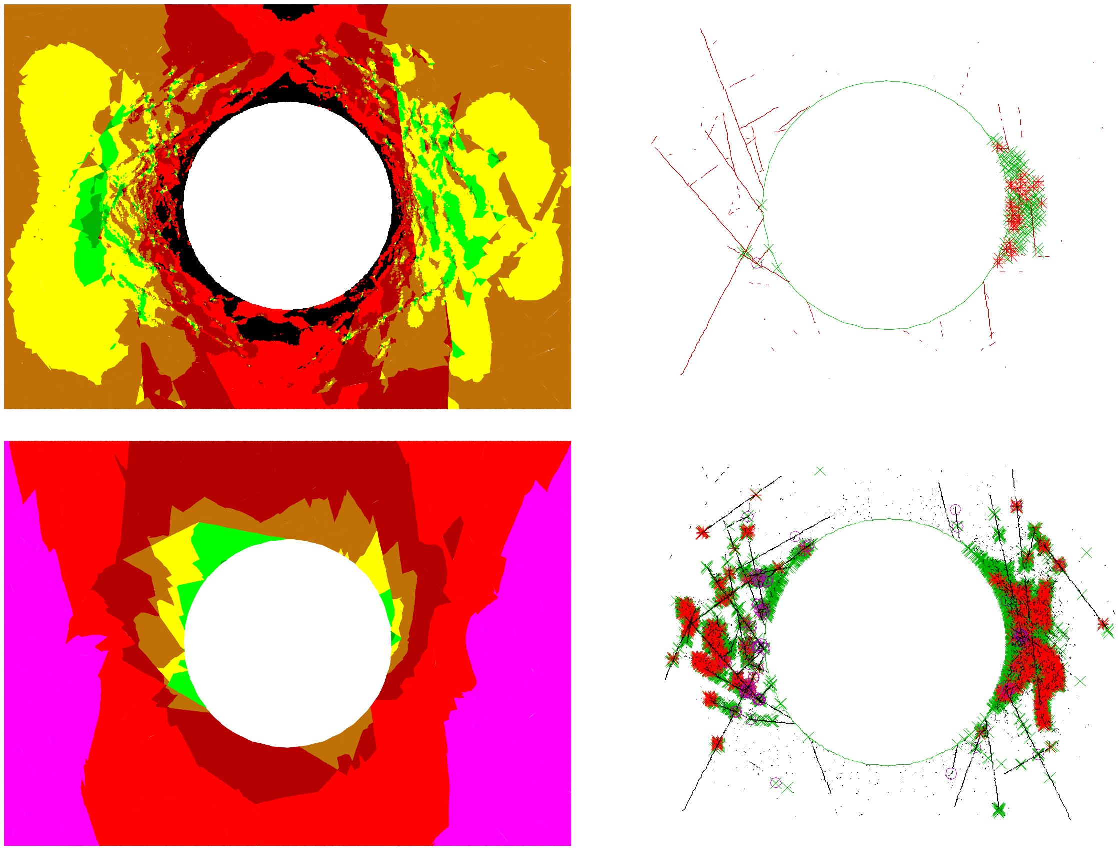

Figure 2: Example of damage identification using stress, deformation and plasticity indicators.

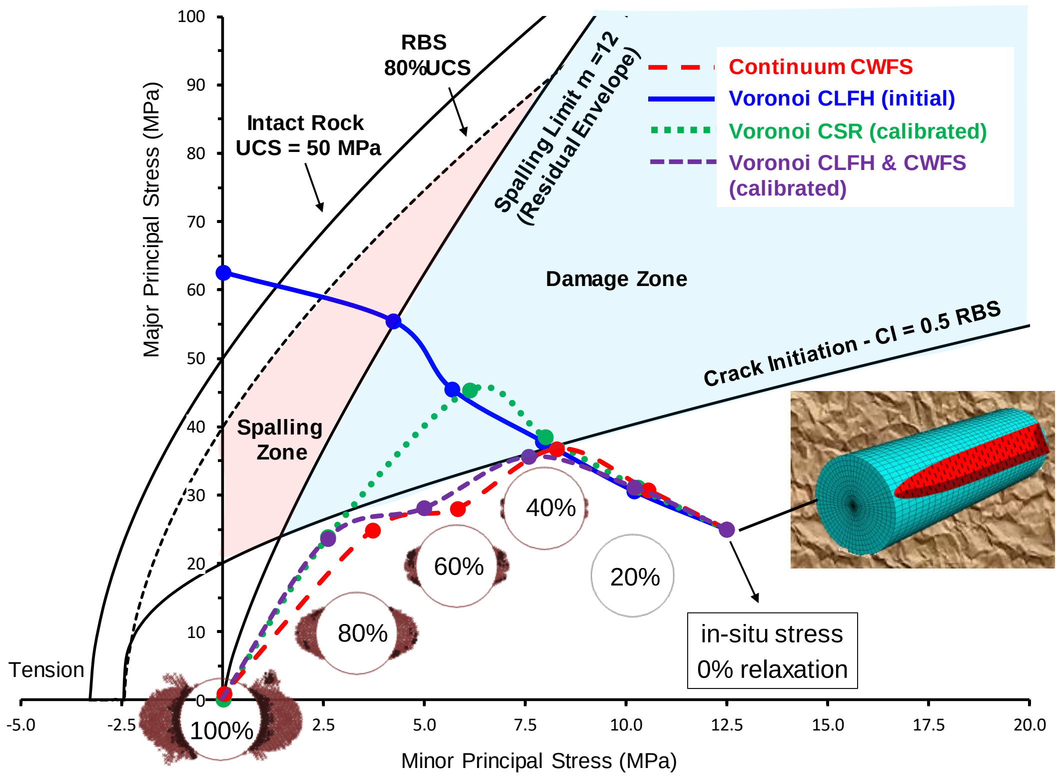

Figure 3: Example of stress paths for tunnel side-wall damage from different modelling approaches.

Session Six: TRANSPORT PROCESSES (Part 1)

Evidence of gas migration processes in Opalinus Clay; The Gas Transport (GT) field study conducted at the Mont Terri Underground Research Laboratory

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Gas is produced in a deep geological repository mainly by metal corrosion of the waste and repository infrastructure. Since the Opalinus Clay is a dense clay-rich host rock and the gas cannot be easily transported away, gas formation causes an increase in pressure that can affect the safety barriers. According to the current state of knowledge, there are four basic gas transport mechanisms in claystone, as shown in Figure 1: (i) gas movement by solution and/or diffusion governed by Henry's and Fick's Laws respectively within interstitial fluids along prevailing hydraulic gradients; (ii) gas flow in the original porosity of the fabric governed by a generalised form of Darcy's Law, commonly referred to visco-capillary (or 2-phase) flow; (iii) gas flow along localised dilatant path-ways (micro-fissuring), which may or may not interact with the continuum stress field, the permeability of which is dependent on an interplay between local gas pressure and the effective stress state; and (iv) gas flow along macro fractures similar in form to those observed in hydrofracture activities during hydrocarbon reservoir stimulation, where fracture initiation occurs when the gas pressure exceeds the sum of the minor principal stress and tensile strength.

The diffusion of gases through clay-rich rocks is relatively well understood and can be easily modelled to predict how the repository system will behave after closure. Considerable effort in recent years has been placed on understanding the advective transport of gas, which can occur if diffusion through the host rock is insufficient to keep the gas pressure low. The primary aim of the GT experiment (Evaluation of gas transport models and of the behaviour of clay rocks under gas pressure) is to gain definitive evidence of whether mechanism (ii) or (iii) are the dominant advective gas transport mechanisms. Experiments in Callovo-Oxfordian Claystone as part of the Euratom FORGE project clearly showed that dilatancy controlled pathways predominated (Cuss et al., 2014).

The GT experiment was initiated to observe the advective movement of gas through OPA. A complementary two-tier approach was adopted with a series of closely constrained laboratory experiments conducted at the British Geological Survey helping to define a field experiment at the Mont Terri underground research laboratory in Switzerland. Both experimental programs were designed to observe the coupling of stress, strain, and pore pressure during the movement of gas.

Four laboratory experiments were conducted: two with the long-axis of the test sample parallel with bedding and two perpendicular to bedding. Figure 1 summarises the main observations of the experiment, with strain observed predominantly perpendicular to bedding, with minor strain parallel to bedding. This was the case no matter the direction of gas flow. It was seen that gas flow was favourable along the pre-existing bedding planes.

The field experiment was constructed in Gallery 08 at Mont Terri in November 2020 with a central injection borehole surrounded by eight monitoring boreholes, as shown in Figure 2. All 8 monitoring boreholes had fibre optic (FO) cabling, with two boreholes having extensometers (Ext), one having extensometers and inclinometers (ExtInc), and one borehole monitoring pore pressure (Pp). After a period of stabilisation and hydraulic testing, a gas injection test was initiated in September 2022. Gas pressure was raised from a starting value of 0.5 MPa up until gas entry in 0.5 MPa gas ramps. Each ramp lasted two weeks and pressure was then held constant for a further two weeks. Gas peak pressure was reached in May 2023 at a magnitude of 4212 kPa, with the first signs of gas entry occurring between 4100 and 4200 kPa. Coupling was seen between pore pressure, strain (extensometers and inclinometers; and fibre optics), and gas injection pressure. Close examination of the response seen at gas entry shows that gas movement was directional and not evenly distributed around the injection borehole.

Dilatant strain was seen in both the laboratory and field experiments when gas first began to enter the Opalinus Clay. These strains were small and had associated changes of pore pressure. In this presentation we present the evidence for the mechanism of gas movement and the causes of the observed coupling.

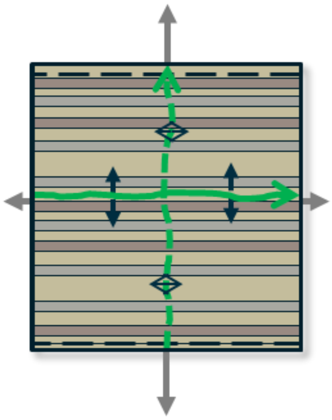

Figure 1: Cartoon of observed strain during gas movement in the laboratory

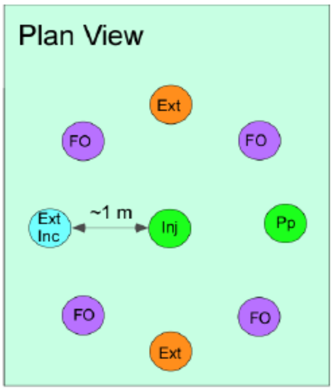

Figure 2: Layout of the GT field test

Cuss, R.J., Harrington, J., Giot, R., and Auvray, C. (2014) Experimental observations of mechanical dilation at the onset of gas flow in Callovo-Oxfordian claystone. In: *Clays in Natural and Engineered Barriers for Radioactive Waste Confinement*; Norris, A., Bruni, J., Cathelineau, M., Delage, P., Fairhurst, C., Gaucher, E.C., Hohn, E.H., Kalinichev, A., Lalieux, P, and Sellin, P. (Eds), **400,** *Geological Society Special Publications*: London, United Kingdom, Geological Society of London, pp. 507-519, doi:10.1144/SP400.26

Multi-phase flow modeling at the component level for the Swiss deep geological repository

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In a deep geological repository for radioactive waste, anaerobic corrosion of various metals lead to the formation of hydrogen. In Switzerland, the implementor is commissioned to describe and evaluate safety-relevant processes related to gas that can affect the long-term evolution of low- and intermediate-level waste (L/ILW), high-level waste (HLW) and combined L/ILW and HLW repositories. Key tasks include the evaluation of gas/radionuclide release pathways and the pressure and temperature evolution in the repository using multi-phase and multi-component flow and transport models.

The Swiss repository design foresees the installation of multiple seals (engineered barriers) in the repository: (i) the V1 seals next to the waste emplacement caverns/tunnels; (ii) the V2 seals located in the access tunnels toward the emplacement caverns/tunnels; and (iii) the V3 seals positioned in the shafts of the repository. These seals are designed to satisfy a wide range of requirements, including requirements related to the hydraulic evolution of the repository and the associated transport of gas, water, and radionuclides.

A workflow is currently being developed, integrating modeling performed both on the repository scale using site-specific models and on the component scale using semi-generic models. The repository scale models are built to assess the thermo-hydraulic evolution in the entire repository, whereas the component scale models allow for more detailed evaluations of the gas and water flows in key structures of the repository, such as the V1, V2, and V3 seals as well as the emplacement caverns/tunnels (see example models in Fig. 1 and Fig. 2). This conference contribution describes the methodology and workflow developed to integrate these models with focus on the development and functionality of the component scale models.

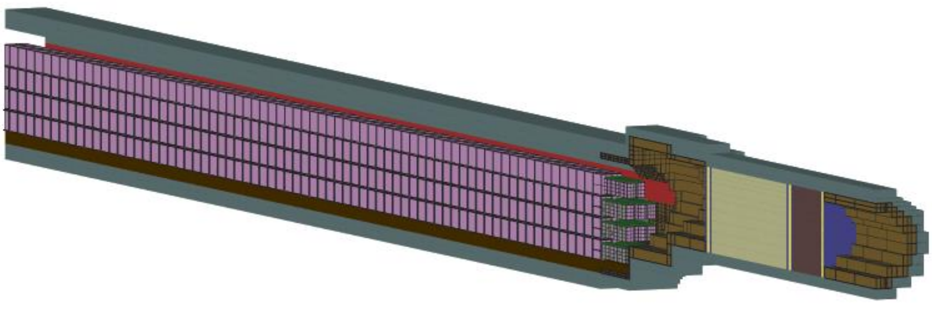

Figure 1: L/ILW cavern model with waste packages

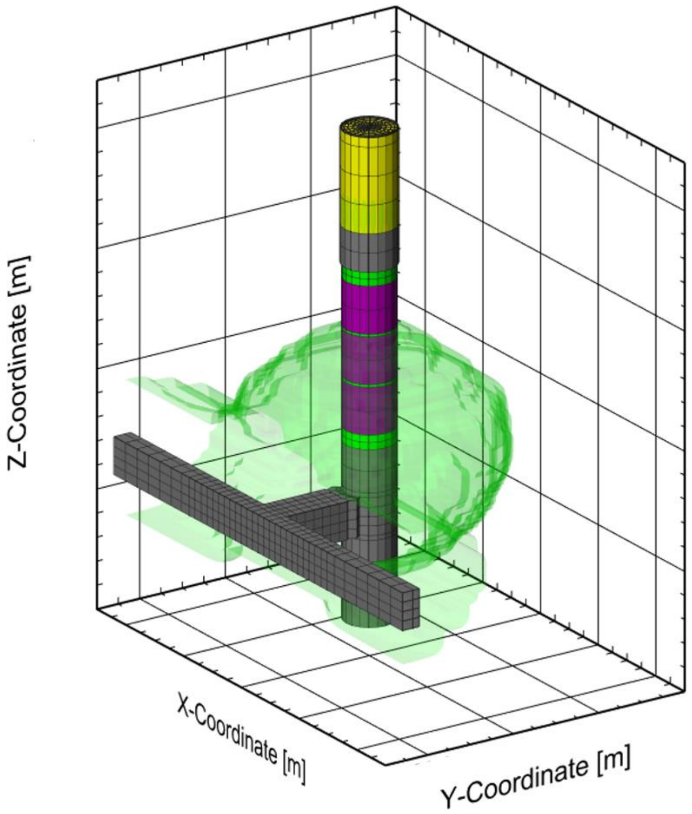

Figure 2: V3 seal model with simulated gas front

Diffusion measurements in natural and synthetic rocks: lessons learned and some relationships identified

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The rate at which diffusion can dissipate the accumulation of generated gases is an important consideration in their treatment within a safety case for the geological disposal of radioactive waste. Understanding variations in the diffusive transport of gas through the host rock and overlying strata therefore emerges as a key factor in the treatment of gas in repository settings. To better understand processes impacting gas diffusion, a series of bespoke experiments, performed on natural and synthetic samples has been undertaken at the British Geological Survey (BGS). The natural samples (Boom Clay) were subjected to an isotropic stress field, undertaken at a reference compaction state (circa depth of burial 400 m). In these tests the role of anisotropy was examined by performing measurements both normal and perpendicular to bedding. Alongside the natural samples, a complementary suite of experiments on synthetic samples has also been undertaken. In these tests the diffusion coefficient to helium gas was determined as a function of mineralogy and bulk density, to explore the impact on the measured diffusion coefficient.

In undertaking this study, a robust methodology has been developed for determining the intrinsic permeability and gas diffusion behaviour of both natural and synthetic samples under representative repository stress conditions. A technique has also been developed to manufacture synthetic samples which have been used to explore some of fundamental couplings between material properties without the complication of heterogeneity of natural materials. Even so, synthetic and natural Boom samples exhibited commonalities in behaviour, with both showing a coupling between intrinsic permeability and measured diffusivity. This coupling appears intuitive as gas diffusion and hydraulic permeability of a sample will always be biased by the connectivity and aperture of larger pores.

Hydraulic data suggests Boom Clay has a permeability anisotropy ratio of around 4.5 for samples tested at the target depth of 400m. While this value will change as more data becomes available, it demonstrates the potential impact of stress history and burial depth, as this value is higher than those previous measured at depths of around 220m. Data suggests gas will preferentially diffuse parallel, rather than perpendicular, to bedding and appears fundamentally linked to intrinsic permeability, Figure 3. Over the data range tested, a semi-log relationship was found to exist which is consistent with previous work linking permeability to changes in effective stress. The coupling between intrinsic permeability and diffusion coefficient was much clearer in the synthetic sample data, showing grain/porosity size distribution, diffusion coefficient and permeability are fundamentally linked. The observation that the fitted functions have similar gradients suggests the same processes governing flow (advection or diffusion) occur in test materials. Given this commonality, it seems reasonable that the trendline derived for Boom Clay could be extended to predict likely diffusion coefficient values for higher/lower permeability samples. However, to do this robustly and with confidence would need more experimental information than was available for this study.

Figure 3 shows a composite plot of all the data measured in this study. By plotting on logarithmic scales, the data from the Eigenbilzen Sands and Boom Clay appear to follow similar trends. This could be coincidence as could the fact data from natural materials and synthetic samples also share very similar power law relationships. However, such relationships should be used with caution. More experimentation is required to check the validity of these relationships, which remain tentative at present.

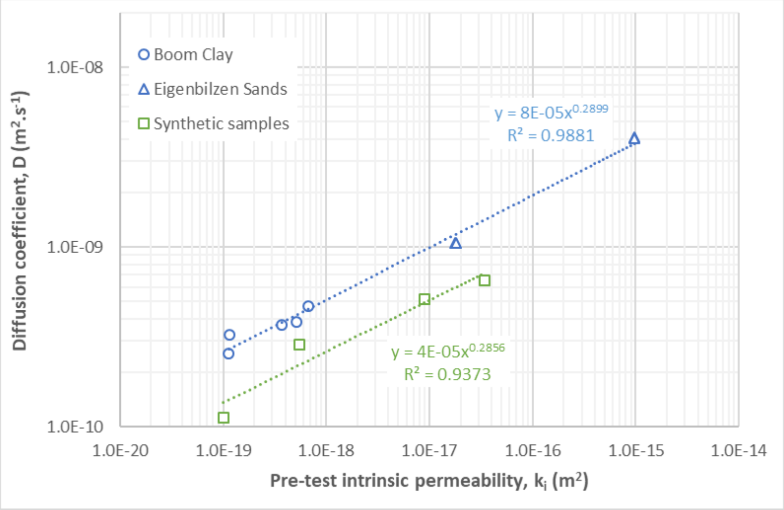

Figure 3: Compilation of data from this study for Boom Clay, Eigenbilzen Sands and synthetic samples.

An initial relationship between diffusion coefficient and bulk density also emerges from this study. This relationship is particularly strong for the synthetic samples whose mineralogy and therefore bulk density are different to that of the Boom Clay samples. As above, while the data indicates a correlation, more experiments are required to add confidence to this relationship and bound the validity of any equations used to predict the diffusion coefficient based on bulk density. As the latter will change as a function of burial depth, it seems likely diffusion coefficients will also decrease accordingly.

This study has successfully measured the permeability and diffusion coefficients for Boom Clay and a sample of the Eigenbilzen Sands under two different stress regimes, and a range of synthetic samples manufactured with different mineralogical compositions, all adding to the knowledge pool for these materials. For the first time, tests on Boom Clay have been performed at an equivalent depth of burial of 400m thus providing new data which, in time, can be used to assess the impact of burial history on the diffusion properties of Boom Clay. While the role of microstructural differences between the synthetic and natural samples needs further consideration and probably accounts for much of the noise in the data for natural samples, this study has also shown the potential for using synthetic samples. These materials can now be refined to yield similar transport characteristics to Boom Clay, providing a useful tool for defining correlations between hard-to-measure parameters (such as the diffusion coefficient). Synthetic samples benefit from being 'pure' systems (without the complicating aspects of natural materials) and can be used to elucidate fundamental relationships more easily.

Preliminary correlations between helium diffusion coefficient and hydraulic permeability have been defined along with correlations between diffusion coefficients and bulk densities. The data also suggests the diffusion coefficient can be linked to other factors including X-ray CT data (e.g., the percentage volume of features above 0.5 mm^3). However, all these relationships required further experimental verification. Diffusion of helium was also shown to occur preferentially along bedding planes with approximately 60% of the diffusional capacity of Boom Clay moving parallel to bedding (which was a key research aim for the project). However, of greater importance was the observed coupling between diffusion and intrinsic permeability which was clear in the synthetic sample data. If correct, such relationships could be used to predict diffusivity across a range of material and permeability scales.

However, before this can occur substantially more experimental evidence is required to improve/disprove these correlations.

EVIDENCE OF ROCK MATRIX DIFFUSION FROM FORTY YEARS OF SITE INVESTIGATIONS IN FINLAND AND SWEDEN

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Rock matrix diffusion (RMD) is the process by which dissolved solutes, moving along flowing fractures, can access the adjacent host rock. RMD was first observed by Brace et al. (1965) while the first theoretical papers were published a decade later (Neretnieks, 1980; Tang et al., 1981). In sparsely fractured rock, RMD, combined with sorption in the rock matrix, is one of the main mechanisms of radionuclide retention and therefore, it is a key process for safety assessment studies for prospected deep geological nuclear waste repositories.

In this paper, we review forty years of site investigation studies carried out in Finland and Sweden focusing on findings and evidence related to RMD. These findings have been obtained mainly from in-situ experiments carried out at three different Underground Research Laboratories, namely ONKALO in Finland and Äspö and Stripa in Sweden. These field activities include tracer test experiments (e.g. TRUE and TRUE block scale at Äspö) and in-situ diffusion experiments (e.g. LTDE-SD at Äspö, the diffusion experiment at Stripa and the REPRO at ONKALO). These field experiments were further supported by a large number of complementary laboratory characterization studies, including a thorough characterization of the pore size distribution of the rock matrix down to the 10^{-5} m scale and by in-situ electrical resistivity methods. All of this extensive experimental work shows no evidence of mechanisms that could limit the penetration depth of RMD to centimeter scale. In some rock types, such as veined gneiss, the existence of nanometer-scale pore throats, together with the presence of negatively charged minerals, can affect the diffusion of negatively charged species. This phenomenon, known as anion exclusion, was observed in the water phase diffusion experiment (WPDE), performed at ONKALO as part of the REPRO experimental programme (Figure 4), where the magnitude of the Cl36 tail of the breakthrough curve was significantly lower than that of HTO (Poteri et al., 2017; Trinchero et al., 2020).

The field and laboratory results discussed here indicate that there is a robust and consistent body of evidence supporting the central role of RMD for radionuclide transport and retention in the fractured crystalline media considered in this paper. Indeed, the site-specific studies presented here show that the connected porosity of the intact rock matrix extends far from the fracture wall with no evidence of spatial limitation.

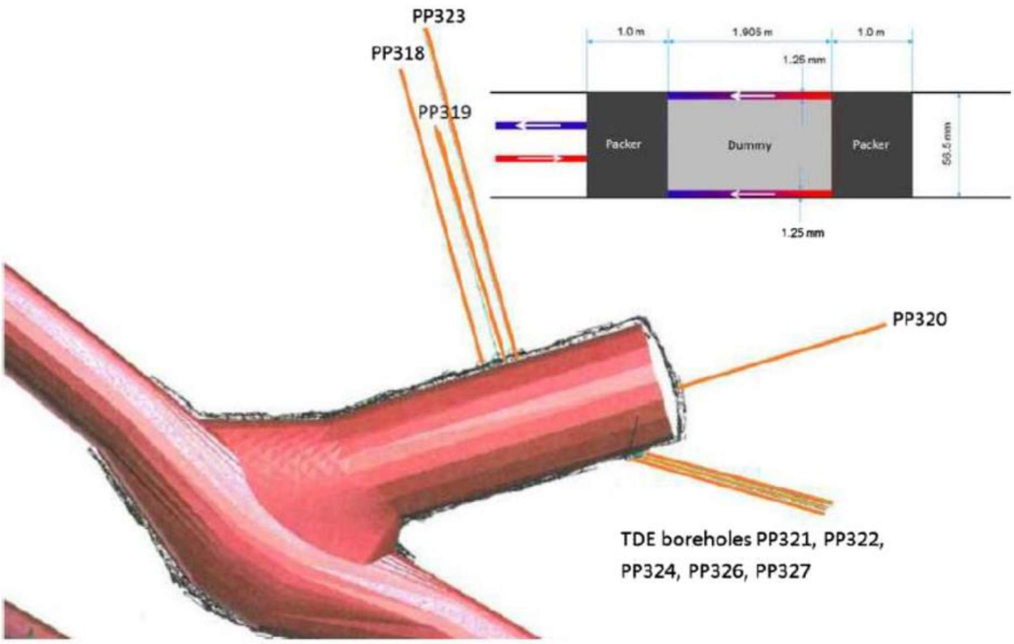

Figure 4 *The REPRO niche located at the 401 m level at the underground rock characterisation facility of ONKALO Finland). The orange lines show the different drillholes drilled from the niche wall. The drillhole ONK-PP323 was used to carry out the Water Phase Diffusion Experiment (WPDE). A sketch of the WPDE experimental setup is shown in the upper right corner. In this sketch, the arrows show the circulating water, the red line on the left shows the injection point whereas the blue line shows the extraction point. The experimental domain is located far away from flowing fractures and therefore is representative of the unaltered rock. Figure modified from Poteri et al. (2017) and Löfgren and Nilsson (2019).*

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Understanding the pore structure of mudrocks for predicting porosity, flow, and transport in host rocks for radioactive waste disposal

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To assess the feasibility of mudrocks as a host rock for radioactive waste disposal, the pore structure needs to be characterised in detail. We here quantitatively analysed the pore structure on 13 sets of mudrocks from across the globe at a broad pore scale range (~ 2 nm to ~ 5 µm) using small angle neutron scattering (SANS). These >70 individual samples differ in age, mineralogy, maximum burial depth, organic matter content, or depositional environment.

We developed a normal cumulative density function model to predict porosity as a function of maximum burial depth. The model allows understanding porosity reduction independent of depositional and post-depositional processes, like compaction and diagenesis. We further conducted multivariate statistical analyses consisting of principal component analysis and multilinear regression to identify and assess the contribution of controls on the pore structure.

The interplay between mineralogy, organic matter, and compaction contributes to a pore network of few-to-several nano-Darcy permeability in which pore size dependent transport mechanisms can vary from transitional transport in micro- and mesopores to slip flow in meso- and macropores and continuum/Darcy flow in progressively larger macropores. Based on the SANS data obtained, we developed fractal models to integrate Darcy permeability with continuum/Darcy flow, apparent permeability with slip flow, and effective diffusion coefficients with diffusion flow for the relevant pore sizes in mudrocks.

We will discuss that improved fluid dynamic models at the pore scale, by incorporating pore structure data obtained from SANS are necessary to understand flow and transport of gases, fluids, and radionuclides in mudrocks relevant for radioactive waste disposal.

Session Seven: WASTEFORM/ WASTEFORM EVOLUTION

The Evolution of the Supply of Cementitious Materials used to Encapsulate Intermediate Level Radioactive Wastes and Implications for the Geological Disposal Facility

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The UK nuclear industry's baseline technology for treatment of intermediate level radioactive waste (ILW) is encapsulation in cementitious materials within stainless steel waste containers, followed by storage and ultimate disposal in a Geological Disposal Facility (GDF), when it becomes available. It is currently expected that the GDF will then be backfilled with a cementitious grout. These encapsulant technologies have been based on Portland cement (PC) with a high replacement of supplementary cementitious materials (SCMs). NNL (and its predecessor organisations), were key in developing these baseline technologies in the 1980s as pulverised fuel ash-Portland cement (PFA/PC) or ground granulated blastfurnace slag-Portland cement (GGBS/PC) encapsulation grouts. In parallel the Nirex Reference Vault Backfill (NRVB) was formulated by other organisations using PC, hydrated lime, and limestone (LS). These cementitious materials were chosen as they are versatile, cost effective, easy to apply, stable over the required timeframe, provide chemical buffering and sorption of radionuclides to retard their release, and are compatible with a cement based GDF.

However, UK net-zero carbon emission targets mean that as a significant contributor, the UK cement industry must reduce its CO_2 emissions. To meet this goal, the UK cement industry is currently moving from PC to lower PC content binary and multicomponent cements. This trend is coupled with the increasing scarcity of the traditional GGBS and PFA SCMs, which themselves are affected by global net-zero trends, with lower carbon methods of steel production and closure of coal-fired power stations reducing their availability.

It is therefore certain that over the coming decade, significant changes will be required in formulating encapsulation grouts, as well as impacting on the materials available for the GDF backfill grouts, and materials to construct the GDF itself. To this end, NNL's Disposal Core Science Theme alongside Nuclear Decommissioning Authority and Site Licence Company funded work, is leading the research into lower carbon PC based systems available today (such as Portland limestone cement, PLC), and limestone calcined clay cement (LC^3), as well as alternative cementitious systems. These alternative cements include geopolymers, calcium sulfoaluminate (CSA) cement, and magnesium phosphate cement (MPC), which while providing specific chemical and performance benefits over the traditional PC-based encapsulants with certain waste types, also have lower carbon footprints and therefore are consistent with a net-zero strategy.

This paper presents an overview of research undertaken by NNL in the past to develop the current generation of cementitious materials used in encapsulation and work performed on the GDF vault backfill. It then moves on to define the new generation of mainstream PC-based cements, as well as the alternative cements. These changes are presented in the context of the implications of geological disposal of encapsulated waste, GDF vault backfill, and also the construction of a GDF.

Discrete event simulation of spent fuel assembly packaging into disposal canisters for the purpose of deep geological disposal

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In the course of 2024, the Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) is going to submit a general license application for a deep geological repository for all types of radioactive waste at the Nördlich Lägern siting region. Thereafter, the current repository concepts will be iteratively refined with a view to the subsequent construction license application and to the realisation of an in-situ underground rock laboratory. Accordingly, a set of workflows and tools is being developed to ensure effective and efficient optimisation of the current reference configuration from 2024 onwards.

The thermal characteristics of spent fuel assemblies represent key constraints to the architecture and design of the deep geological repository with its main components and processes, as well as to various pre-disposal activities. Currently, it is envisioned to encapsulate spent fuel assemblies into final disposal canisters of about 1 m in diameter having a maximum thermal load of about 1,500 W. This requires a dedicated encapsulation facility, of which a general licence application will also be submitted in 2024.

With a view to the optimisation of the entire chain of facilities and activities for the safe disposal of spent fuel, a discrete event simulation model for the packaging of spent fuel assemblies into disposal canisters has been developed and applied. The model includes all major components and processes of the planned encapsulation facility along with the main spent fuel assembly characteristics, which consist of their time-dependent thermal power and their associated location (transport and storage cask ID) during dry interim storage. Moreover, the model accounts for the limited capacities of both human and non-human resources and implements a simplified worker shift scheme. Besides being able to fully simulate and verify the current reference configuration, the model is also capable of accounting for large variations of key design choices, such as the start time of packaging operation, the disposal canister size, the thermal limit per disposal canister size or the number and capacity of key resources.

The discrete event simulation model is complemented by a simplified cost model that estimates the total cost of interim storage, packaging and transport of spent fuel assemblies as a function of the mentioned key design choices and the associated simulation model's output. To identify the most critical parameters for important output indicators, such as total number of disposal canisters, packaging duration or total cost of storage, packaging and transport, both local and global sensitivity analyses methods have been successfully applied.

Our presentation will provide an overview of the Swiss disposal context, describe the key features of the discrete event simulation model and discuss key results and their implications on upcoming steps in the Swiss disposal programme.

Will sizing down scale up the problem?

A perspective on how waste arising from Rolls Royce SMR and GE-Hitachi BWRX-300 SMR could impact future disposability.

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Small Modular Reactors (SMRs) are defined by the International Atomic Energy Agency (IAEA) as small-scale reactors that have a lower electrical output compared to their full-scale counterparts. Due to their size, SMRs are anticipated to provide benefits in construction, operation, and economics as they can be substantially manufactured in the form of modular units that are later assembled on site [1] [2]. Water-cooled SMRs are scaled down versions of existing commercial Light Water Reactors (LWRs); Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs). Six companies' SMR designs have been shortlisted in the Great British Nuclear (GBN) technology selection process: EDF (Nuward), GE-Hitachi (BWRX-300), Holtec (SMR-160), NuScale Power (VOYGR), Rolls-Royce SMR and Westinghouse (AP300) [3]. Out of these, the GE-Hitachi BWRX-300 is a BWR design, and the Rolls-Royce SMR is a PWR. For any reactor, waste management must be demonstrated at the design and/or licencing stage in the interest of protecting public health and the environment from ionising radiation and other hazards. This is achieved by ensuring compliance with international and UK standards, guidance, best practice and legislation such as Best Available Techniques (BAT), As Low As Reasonably Practicable (ALARP, for worker radiation doses) and the waste hierarchy.

Full scale LWRs produce liquid effluent from the purification of the primary coolant and processing of effluents via techniques including ion exchange, filtration and evaporation [4]. The LWR-based SMR designs will need to carry out the same processes, however the BWRX-300 will benefit from a potentially zero liquid effluent emission due to its single primary reactor coolant water circuit. In the case of the Rolls-Royce SMR, the design intent is for 'minimal liquid discharge', a design and operational approach which will preferentially reuse and recycle effluents within the plant, with discharges to the environment under permit only taking place under certain circumstances. This will be enabled by high-efficiency, multi-stage processing systems which will output solid wastes such as spent ion exchange resins and sludges in common with full-scale LWR. The volume of liquid effluent produced by SMRs is expected to be significantly lower in proportion to the smaller size of the reactors. In terms of spent nuclear fuel (SNF), older generation technologies such as AGRs (Advanced Gas-Cooled Reactors) and legacy Magnox reactors achieved much lower fuel burn-up rates and hence produced a higher amount of SNF based on a thermal load equivalent. The new SMRs (whether based on existing LWR technology or innovative Generation IV technologies) are intended to meet energy needs whilst bringing benefits in terms of efficient fuel use, lower waste production, improved economics and high sustainability metrics. The IAEA stated in 2019 that fuel from SMRs based on current technology can be managed via existing methods and infrastructure [1], and both the UK Rolls-Royce SMR and BWRX-300 use industry standard uranium-oxide fuel that is already well understood and will be compliant with the planned UK Geological Disposal Facility (GDF).

However, research conducted by Stanford University in 2022 [5] concluded that the proposed ‘cost and safety advantages’ of SMRs may be overshadowing the challenges of nuclear waste management and disposal arising from these technologies. The study assessed different proposed SMR designs; a PWR, sodium-cooled fast reactor, and a molten salt reactor. These designs were compared at the end of their nuclear fuel cycle against a 1,100 MWe PWR through conducting comparisons of SNF and Low/Intermediate Level Waste (LILW) energy equivalent volumes, radiochemistry decay heat and fissile isotope composition of waste streams. The study has suggested there could be an increase in the volume of waste by a factor between 2 to 30, compared to LWRs, and several of the technologies may produce waste streams which are unsuitable for direct geological disposal due to high susceptibility to nuclear criticality [5]. The study also proposed that the SMR designs would have a higher neutron leakage and thermal flux due to their greater surface area to volume ratio. Resulting in increased activation of primary circuit structural materials, along with lower fuel burnup producing more high active waste [5] [6]. The study considers a range of technologies with very different characteristics (i.e., coolant and fuel types), and therefore does not give full credence to the technologies which are highly derivative of existing LWR technologies (and which will therefore not result in ‘exotic’ wastes) and is largely based on speculative and theoretical calculations. Therefore, this area requires further investigation, potentially with greater focus on particular technologies, to more robustly assess the performance of SMRs against existing technologies.

The presentation will include descriptions and explanations of the key radioactive waste streams that will be generated from water-cooled SMR designs, along with the currently proposed approaches for waste processing and immobilisation. It will also cover how the waste strategies are being formulated to minimise volumes of primary and secondary wastes whilst achieving BAT/ALARP, how it will be ensured that all waste packages produced will be compatible with the UK GDF, and what the challenges likely to be faced now and in the future will be.

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Session Eight: RELATED INITIATIVES

Session Nine: MONITORING

Confidence in Repository Monitoring Data - Key Results from the MODATS Work Package of EURAD

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Repository monitoring is motivated by the desire to inform decision making, strengthen understanding of system behaviour and to build further confidence in the repository safety case. The Monitoring Equipment and Data Treatment for Safe Repository Operation and Staged Closure (MODATS) work package (WP) of the European Joint Programme on Radioactive Waste Management (EURAD) conducted research, development and demonstration (RD&D) into monitoring, focusing on monitoring during the operational phase of repository programmes to build further confidence in the long-term safety case. For monitoring to support building of further confidence in the long-term safety case requires that the data produced by the monitoring programme can be relied on, and can be used in analysis, decision making and communication.

There are particular challenges to establishing confidence in data for these uses. These challenges are mainly related to the long timeframes over which the monitoring programme might operate, and the requirement that monitoring programmes are designed and implemented so as not to reduce the overall level of safety of the repository after closure.

MODATS has developed understanding of how confidence can be established in monitoring data so that it can support the long-term safety case. This has included development of:

- Knowledge on the performance of monitoring equipment through a survey of underground research laboratory experiments.
- Guidance on quality assurance across the lifetime of the repository monitoring programme.
- Methods for data management, modelling and visualisation, which has included an understanding of how anomalies in data can be identified and treated, developments in the use of machine learning to provide modelling approaches based on data science, and developments in visualisation to facilitate additional learning from monitoring data.
- Pluralistic methods for engagement with public stakeholders.
- Advanced monitoring technologies, including fibre optic systems and geophysical methods and research into new monitoring methods.
- A formal approach to the way in which monitoring equipment could have an impact on post-closure performance.
- A roadmap for the development of monitoring technologies.
- Approaches to knowledge management linked to the approaches developed in the wider EURAD programme.

This presentation provides a high-level summary of the key findings of the RD&D in MODATS relating to confidence in repository monitoring data.

Session Ten: ENGINEERED BARRIER SYSTEM

Hydromechanical behaviour of bentonite clay at temperatures greater than 100°C

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The physical footprint for a UK Geological Disposal Facility (GDF) will be controlled by the volume of waste emplaced and the selected spacing between waste cannisters. Current spacing estimates for High Level Waste (HLW) assume that a conventional maximum temperature, T, of 100°C is imposed on the bentonite clay designed as an engineered barrier surrounding the waste canister. Whilst limited information is available on the behaviour of these materials above this threshold, being able to demonstrate safe conditions at higher temperatures would allow a GDF footprint to be reduced, resulting in substantial technical and cost benefits. Over the past 5 years, the European Joint Framework on Radioactive Waste Disposal (EURAD), has included a large work package (HITEC) examining the impacts of higher temperatures on both engineered barriers and host formations. A key focus of this collaboration was to assess the impact of elevated temperatures (up to 200°C) on GDF safety functions. We present findings from an experimental programme conducted within HITEC by the British Geological Survey, which was designed to examine the hydromechanical behaviour of pure bentonite clay between 100 and 200°C.

Experiments were conducted on pre-compacted samples of MX-80 Bentonite (VolClay), which is a fine-grained sodium bentonite, from Wyoming (USA), containing around 90% montmorillonite. Shorter samples were compacted at the BGS, using powder supplied by Sibelco Nordic, who crushed and dried the material. Manufacture involved mixing bentonite granules with deionised water and compressing in a mould under a one dimensionally applied stress. Longer samples were manufactured by Clay Technology AB (Lund, Sweden), using a similar methodology (Johannesson et al., 1995).

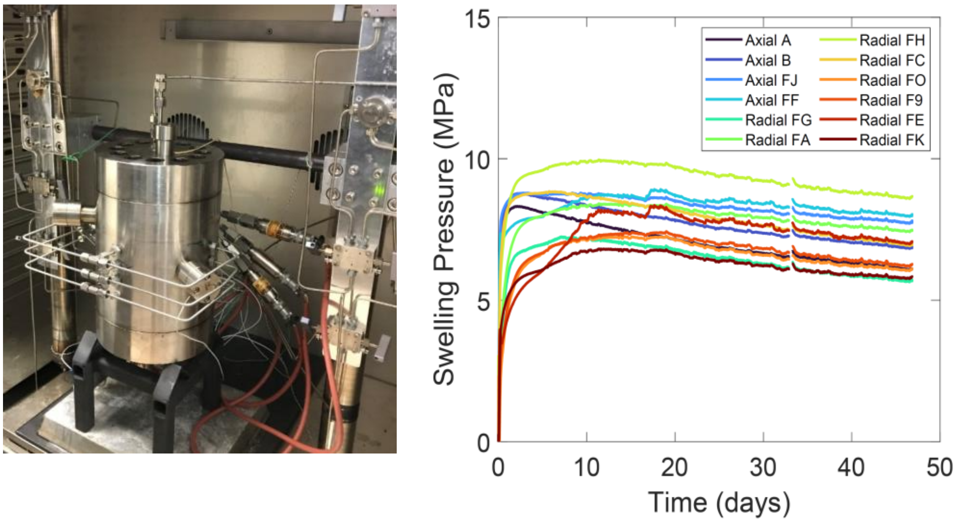

Figure 5. (Left) High temperature constant volume test apparatus used for hydraulic permeability thermal cycling. (Right) Swelling pressure development measured in Mx80 bentonite in multiple locations at 175°C.

Two bespoke apparatus were designed and constructed at the BGS for the purposes of the test programme. These were designed to examine: (i) the impact of bentonite swelling pressure on temperature under constant thermal conditions and (ii) the functional dependency of swelling pressure and hydraulic permeability during thermal cycling. In both cases, testing was conducted under constant volume conditions for several dry densities (1.3-1.7 g/cm^3). In additional constant thermal tests, shorter samples were used, resulting in axial swelling during testing, reflecting the behaviour of voids contained with the engineered barrier. In both cases, the pressure vessel assemblies were housed within an oven and allowed to reach an initial target temperature before a test sample was inserted into the vessel. An array of sensors surrounding the sample enabled stress field development to be monitored during hydration and swelling. Deionised water was used to hydrate test samples through two porous filter discs, embedded in both pressure vessel end-closures. Net flow of water was monitored and controlled by two ISCO syringe pumps. Before testing, extensive calibration of both the pumps and sensor array was carried out, as a function of both pressure and temperature.

Twelve constant thermal tests have been conducted at temperatures of 100, 150 and 175°C. In each case, the sample was loaded into the vessel and a constant applied water pressure of 4.5 MPa was applied to both ends. The resulting swelling pressure evolution was then monitored for a period of between 50 and 100 days. In addition, three thermal cycling tests have also been conducted. These involved the initial hydration of the sample at an applied water pressure of 2 MPa. Once measured stresses had reached a plateau, a constant pressure head (4 MPa) was applied to the upstream end of the sample, inducing hydraulic flow and enabling permeability measurement. Temperature was then cycled in a series of steps (100, 150, 200, 150, 200, 150, 100°C), which were each held long enough to allow hydraulic permeability to be remeasured.

In most cases, significant heterogeneity remains apparent in the final swelling pressure distributions, even after 50 days (Figure 1). This heterogeneity is substantially greater in those samples where axial swelling was permitted, even after 100 days. As expected, in all cases, significantly higher swelling pressures were generated for higher dry density samples. Measured swelling pressure was seen to reduce with increasing temperature (100-175°C) for dry densities of 1.6 and 1.7 6g/cm^3 (Figure 1). This was also the case in tests where axial swelling was permitted (dry densities of 1.5g/cm^3 and 1.7g/cm^3). Nevertheless, the lower dry density samples (1.3g/cm^3) were found to be comparably insensitive to temperature. For those tests where a swelling pressure reduction was observed, a notable temporal degradation was also apparent, though this was not seen for the lower dry density tests.

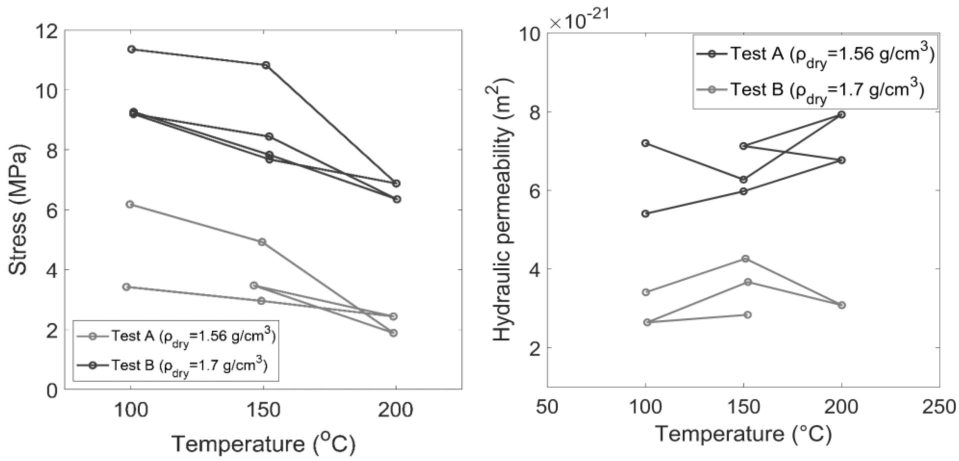

Figure 6 (Left) Total stress evolution and (right) hydraulic permeability evolution, as a function of temperature during thermal cycling.

Observations from the thermal cycling experiments indicate that this reduction in swelling pressure is hysteric and not recovered on unloading (Figure 2). However, minimal changes in hydraulic permeability were found to occur during thermal cycling (between 100-200°C), despite the observed changes in swelling pressure (Figure 2). The mechanisms for this behaviour remain uncertain but could relate to mechanical changes to the clay during thermal loading. Further work examining the rate and controls on this behaviour would be beneficial to reduce this uncertainty and facilitate the development of engineered materials designed to operate at higher temperatures. These findings also provide process understanding and data for parameterisation of numerical simulations that may be used to assess barrier performance under elevated temperatures.

Interaction of simulant thermally-treated intermediate level wastes with a high pH cementitious backfill

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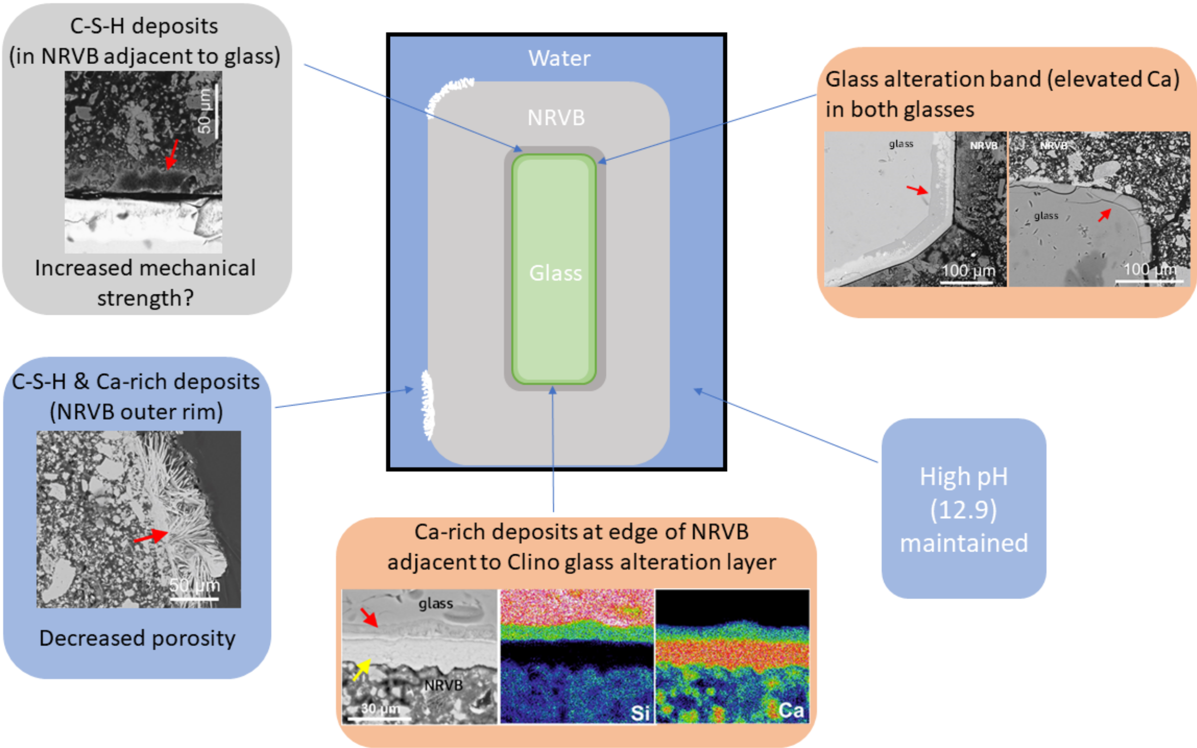
Thermally-treated wasteforms are being considered for the disposal of intermediate-level waste (ILW) within a geological disposal facility (GDF). This requires, in part, assessment of the impacts these potentially new wasteforms may have on the long term evolution of the backfill barrier employed in the UK's GDF. Consequently, an experimental study was performed to assess the impact of two simulant thermally treated ILWs (glasses) on the long term performance of a high-pH cementitious backfill, the Nirex Reference Vault Backfill (NRVB). The experimental setup consisted of monoliths of NRVB with coupons of glass embedded within them. These were submerged in water at 50 ºC (under anoxic conditions) and were cut open periodically over four years to expose the coupon/NRVB interface and reveal any changes resulting from the interactions. A complimentary experimental setup was also utilised that mixed powdered samples of the glasses and NRVB to accelerate the interactions between them. The results indicate that a high pH was maintained and that the systems evolved to form abundant C-S-H phases, which are the major sorbing phases in the backfill for many radionuclides. Overall, the study strengthens the understanding that the potential range of UK thermally treated ILW wasteforms are likely to be compatible with the existing ILW disposal concept using a high pH cement backfill.



A schematic of the interface experiment summarising the major findings.

Bentonite homogenisation and swelling: The effect of salinity

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The universally favoured option for removing intermediate (ILW) and high (HLW) level radioactive waste and spent nuclear fuel (SNF) from the anthropogenic environment is by disposal in geological repositories. Repository designs worldwide incorporate many common features including canisters to contain the waste, sited in deposition holes within a tunnel system that is constructed in a host rock with favourable geological properties. In many cases, high heat generating wastes (HHGW) and low heat generating wastes (LHGW), of which ILW and low-level wastes (LLW) mostly comprise, will be sited in separate parts of a repository or in different locations altogether. For the more radioactive HHGW, a clay buffer is often used in designs for the engineered barrier system (EBS). The same material could also be used as a backfill in tandem with crushed host rock to seal the disposal galleries and prevent access to the waste from the surface environment. The geological repository will need to be able to safely contain HHGWs over a timescale of around 1 million years, and the behaviour and performance of the chosen EBS material will need to be demonstrated before it is selected for use in a UK GDF. The EBS must be able to both limit migration of radionuclides, and ensure canister stability and the closure of high permeability pathways around the canister.

The material most widely considered in radioactive waste repository designs for use in the EBS and backfill is bentonite. Bentonite is smectite rich and as such, has a very low permeability and high swelling capacity. Bentonite is commonly incorporated in repository concepts as precompacted blocks used to fill a void. This configuration necessarily leaves smaller void spaces between the blocks that will need to effectively close to ensure high permeability pathways do not remain. A wide range of different bentonites have been considered for use. Sodium bentonites (such as the Wyoming-type MX80, GMZ bentonite, and Turkish Resadiye) and calcium bentonites (such as the Fourges Clay and the Černý Vrch deposit) have both been studied, due to their naturally good availability for different nations. How quickly the bentonite will evolve to reach its target properties will be controlled by the rate of swelling of the material. This is dependent on the bentonite dry density, fluid availability and composition, the pore pressure magnitude and the waste temperature.

Non-uniform swelling presents a significant challenge to the repository safety case because it introduces anisotropy in the hydromechanical properties, especially if the material heterogeneities persist in the long-term. In addition, the dry density of the bentonite may decrease where there is enough void space into which the bentonite can swell. Thus, the time-dependent development of porewater pressure may lead to localised material heterogeneity in terms of the hydromechanical properties (swelling pressure, permeability, strength and friction coefficients); this has been observed in both laboratory and full-scale experiments. Development of swelling pressure in bentonite is also affected by the porewater chemistry, with increasing salinity of groundwaters correlated with an increase in permeability and decrease in swelling pressure. Recent work has defined a set of reference pore waters for various locations and host formations of interest in the UK (Smedley et al., 2022). In several cases, groundwaters are expected to have very high salinities. This porewater chemistry, combined with the presence of technological voids may present a technical challenge to repository designs involving bentonite.

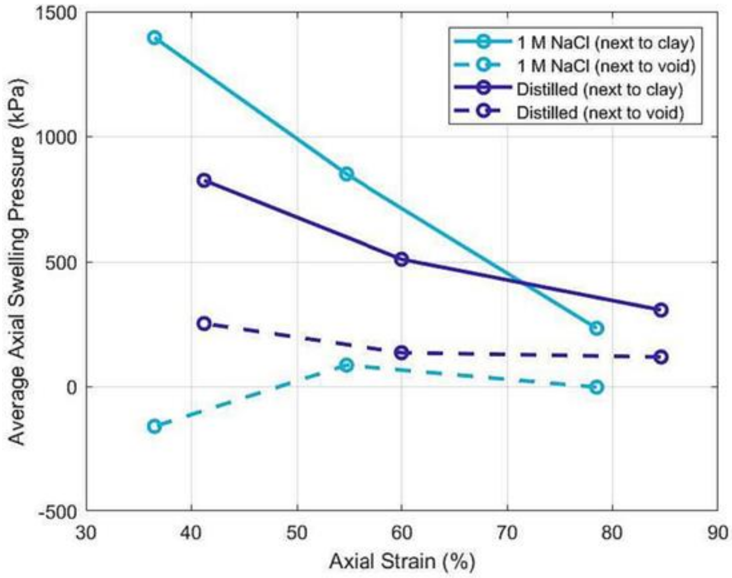

Figure 1: The average axial swelling pressure after 100 days as a function of the axial strain resulting from swelling, compared against equivalent tests conducted by Harrington and co-workers (2020) under zero salinity conditions.

A suite of experiments has been conducted to study the effect of a combination of elevated fluid salinity and the presence of an engineering void space, on the swelling behaviour and subsequent properties of barrier bentonites. The role of axial strain on the homogenisation and swelling pressure development in both sodium and calcium bentonites was examined by varying the starting sample length between experiments, and this has been compared with the zero-salinity case (Harrington et al. 2020) (Figure 1). At the end of each test (at 100 days) the clay had swelled into the void space, demonstrating its capacity to fill even relatively large voids. In some cases, relatively significant residual differential swelling pressures (difference between the maximum and minimum swelling pressure recorded at a given time) were observed. However, for high salinity fluids, the generation of significant swelling pressure in the clay in the low-density end of the sample did not occur during the testing period. Under the same salinity conditions, much smaller peak swelling pressures were observed for the calcium bentonites. The findings of these experiments suggest that the suppression of clay swelling at higher salinities is has the capacity to strongly impact the void-filling process.

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Long-term Thermal-Hydrological-Mechanical Behaviour of Bentonite as a Component of Radioactive Waste Disposal Concepts

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Bentonite has been extensively studied and is recognised as a reliable component of geological disposal concepts, including for radioactive waste, owing to its thermal, hydrological, mechanical and chemical (THMC) properties. Research efforts spanning several decades have focused on investigating its performance under simulated subsurface conditions. End-member laboratory tests (e.g. testing the full range of potential salinities, temperatures and stresses) are necessary due to their ability to quantify specific properties of bentonite efficiently and precisely within appropriate timeframes, providing valuable insights into potential implications and considerations for repository design that would otherwise require extensive and less practicable measurements.

Here we report experimental data on its THM properties to provide a comprehensive understanding of its potential behaviour as a buffer material in long-term geological repositories. We use a combination of rock physics experimental approaches, combined with microstructural observations using microCT imagery, before, during and after deformation. We demonstrate the significance of MX80 bentonite's initial degree of saturation on measured parameters, highlighting the need for blocks to be manufactured with high saturation levels to optimise performance, and we focus on sensitivity of mechanical properties on samples above 95% saturation. The influence of temperature has been examined, revealing that cold subsurface conditions have minimal impact on the integrity of bentonite as an effective buffer for containing radioactive waste. However, the presence of highly saline groundwater during compaction is shown to result in a distinct increase in stiffness, which leads to more brittle behaviour and potential cracking.

Our results demonstrate that bentonite remains highly suitable as a barrier component. Perfecting the manufacturing process,and being as stringent as possible in the preliminary phases of implementation is necessary, with homogeneity and initial degree of saturation playing vital roles in early-stage repository evolution. Initial heating from continued emissions from the spent fuel rods may cause proximal dehydration and desiccation cracks. We see a change in density distribution surrounding these fractures using microCT, but this is expected to equilibrate once groundwater has permeated the surrounding regions through bentonite's self-sealing characteristics. Mechanical strength is strongly governed by the degree of saturation, therefore where dehydration occurs, the localised degree of saturation could promote regions of mechanical weakness. The relationship between strength and saturation also has a distinct dependency on confining pressure, we examine this up to end-member P. of 50 MPa. The direct effects of colder temperatures are confirmed to have no effect on the functionality of the bentonite barrier. A salinity gradient caused by salt exclusion during periods of permafrost could reduce the swelling abilities, and promote erosion of the bentonite barrier.

If saline fluid is eventually introduced, there could be corrosion of the canister. If less saline fluid is introduced, some regions could swell unevenly, and induce stresses on the canister.

Consistent and robust manufacturing processes are crucial to maintain uniform samples, ensuring reliable moisture distribution and preventing potential failure whilst enabling efficient self-sealing through swelling. Controlled interim storage of blocks is imperative to sustain optimal saturation levels, mitigate premature drying and cracking, identify manufacturing defects, and facilitate continuous monitoring for enhanced safety. Some long-term studies have demonstrated that bentonite's swelling and self-sealing abilities are maintained even in challenging environmental conditions, and we examined this using a suite of experiments, combined with CT imagery during in-situ thermal cycling. These findings significantly enhance our understanding of bentonite's role as a constituent of geological disposal concepts, particularly for long-term nuclear waste containment.

KEYNOTE: Candida Lean

Regulating a geological disposal facility and the importance of geological knowledge in the underpinning regulatory submissions

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The Environment Agency will jointly regulate a geological disposal facility (GDF) with the Office for Nuclear Regulation (ONR). We are responsible for ensuring that a future GDF will remain safe for people and the environment during the construction, operation, closure and post-closure phases for as long as a potential hazard remains.

In order for us to permit a GDF, we will require the developer, Nuclear Waste Services (NWS), to prepare and maintain an environmental safety case (ESC) that demonstrates that the GDF will meet the required standard of protection of people and the environment. Our guidance (Geological disposal facilities on land for solid radioactive wastes (publishing.service.gov.uk)) describes the requirements that the ESC will need to address. Key to making an ESC for a GDF is the need to demonstrate that the waste will be contained within the GDF, through a combination of natural and engineered barriers and other environmental safety measures, and disposed of in a stable geological formation to provide long-term isolation of radionuclides from the biosphere.

Understanding of the surface and sub-surface environment is crucial to determine how the site and surrounding area has evolved and is likely to continue to evolve in the future, and to underpin the ESC. We require NWS to carry out a programme of site investigation and site characterisation to provide information to develop an ESC. The outputs from these studies will also support facility design and construction. We expect NWS to establish an iterative approach to site investigation that uses results from site characterisation, modelling studies, design and construction to guide further investigations.

As siting progresses, in order to meet our requirements NWS will need to:

- Carry out non-intrusive site investigations, for example, seismic surveys, to identify potential volumes of host rock.
- Determine baseline conditions prior to any intrusive investigations.
- Carry out intrusive investigations such as drilling deep boreholes.
- Develop conceptual site models of the geology, hydrogeology, geochemistry, geotechnical properties and structure of the potential host rock and the surrounding area, including adjacent and overlying rock that will provide an important barrier to future radionuclide and non-radiological contaminant migration from the GDF and potential locations for accessways and surface facilities.
- Carry out experiments at a variety of scales, and for a range of durations, to investigate the properties of the host rock and overlying rock to aid engineering design, development of the ESC and GDF construction. These should inform the development of package designs and backfill and engineered barrier solutions that are robust to the target host rock. These data will also be crucial to predicting the future evolution of the GDF and the engineered and geological barriers and assessing potential mechanisms for radionuclides and non-radiological contaminants to migrate from the facility.
- Develop environmental safety assessments that will demonstrate that the disposal system and its implementation will provide the required standard of environmental safety during the operational period and post-closure.

- Engage with international radioactive waste management organisations, international organisations such as the International Atomic Energy Agency and the Nuclear Energy Agency, and international research programmes to learn from experience and participate in joint work, ranging from experimental works to modelling studies.

The regulators are not involved in, and are independent of, the GDF site selection process. As a site has not yet been selected to host a GDF, regulators are providing pre-application support and guidance to NWS. The Environment Agency's formal regulatory process for geological disposal will start when NWS has selected a candidate site(s) and wishes to carry out surface-based intrusive investigations such as drilling boreholes. In its permit application, we will require NWS to:

- explain how the intrusive investigation work, including the outputs from the borehole monitoring programme, will inform a future ESC if the candidate site were to be selected for the development of a GDF
- demonstrate that the intrusive investigation work would not compromise the integrity of a candidate site to the unacceptable detriment of the ESC
- explain how the boreholes can be sealed in a manner that provides appropriate environmental protection

Staff with geoscience expertise have a crucial role in the regulation of a GDF, including:

- reviewing NWS's developing site descriptive models for candidate sites, considering geological, geophysical, geochemical, hydrogeological and geotechnical data
- assessing NWS's site characterisation plans for its intrusive investigation programme and monitoring
- reviewing NWS's plans for sealing boreholes so that they do not detrimentally affect the environmental safety of a GDF
- reviewing NWS's developing ESC and safety assessment
- reviewing NWS's underpinning research programme
- ensuring that NWS applies best available techniques (BAT) to GDF development

Session Eleven: TRANSPORT PROCESSES (Part 2)

Thermal-hydro-chemo-mechanical coupled modelling of ionic transport in clay materials

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Compacted clay is considered as an excellent candidate for barriers to radionuclide transport in future repositories for nuclear waste due to its very low hydraulic permeability and high adsorption capability. Assessment of the clays' long-term containment function requires adequate modelling of ionic transport under demanding environment. A Thermal-hydro-chemo-mechanical coupled model based on the truncated octahedron cellular assemblies is developed to simulate ionic transport under different confining pressures, pH and temperatures. The cellular assembly is divided into two interacting graphs: one is the mechanical graph which is developed to describe the deformation behaviour of the material, and the other is physical/chemical graph which is developed to demonstrate the reactive transport in the material. This setting is realistic especially when the mechanically-driven cracking has an impact on the transport pathways. Both graphs can represent the anisotropy and heterogeneity of the materials. The model performance is demonstrated using experimental data on the diffusion of species through Opalinus clay (OPA) – a complex process that involves elastic response, diffusion and anionic exclusion. Calculated diffusion coefficients of HTO and uranium species are within the ranges of the experimentally determined data in different clay directions.

A REVIEW OF THE STATE OF THE ART IN REDOX AND KINETICS APPLIED TO NUCLEAR WASTE DISPOSAL FACILITIES

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Geological radioactive waste repositories are based on the 'multiple barrier principle', in which long-term safety is assured by a series of engineered (EBS) and natural barrier systems. In the multi-barrier system of a repository there will be a number of redox-active components and aqueous species that will influence redox conditions. Characterization of redox potential in the disposal facilities both in the near- and far-field is needed to understand adequately the migration of redox sensitive radionuclides and chemical pollutants in the context of deep geological and surface disposal systems. The redox potential of a geochemical system is controlled by both the thermodynamics and kinetics of redox reactions including abiotic and biotic processes, such as microbial catalysis. The redox potential strongly influences the mobility of redox-sensitive contaminants, such as U, Np, Pu, Tc, Se, Mo, or Sb among others (Guillaumont et al. 2003; Ma et al. 2019; Olin et al. 2005). The reduction of these elements into lower redox states, generally results in increased retention due to the precipitation of low-solubility solid phases. However, the behaviour is different for Pu, whose +III oxidation state is characterized by greater solubility and weaker sorption than the +IV counterpart.

For natural systems, microbes have the potential to catalyse and accelerate the kinetics of chemical reactions. Even though, the microbial activity is expected to be limited under the near-field conditions, mainly due to high radiation dose and bentonite low water content, microbes may flourish in pockets where adequate conditions develop during the lifetime of the repository.

To improve the EBS materials and their designs, the different occurring redox processes, must be carefully investigated and understood. This would ensure the longevity of EBS and their capability to retain radionuclides and chemical pollutants.

With this motivation, a review of the State-of-the-Art in redox and kinetics applied to surface and geological disposal facilities is developed in the framework of ThermoChimie Consortium (Andra, NWS, ONDRAF/NIRAS).

Due to the characteristics of nuclear waste disposal facilities, the main redox couples expected to control the Eh value of a geological disposal system are those of Fe (II, III) and S (VI, -II). Steel and its corrosion products will be major components of any geological disposal, having the capability to buffer the repository against any potential oxidant intrusion (Duro et al., 2014). Iron corrosion under both oxid and anoxic conditions is a process kinetically controlled and the corrosion rates are influenced by different parameters (pH, composition of the material, temperature, groundwater composition, presence and composition of gases, and evolution of the surface). Corrosion products may form a protective layer on the steel surface and cause a decrease of the corrosion rate with time (Smart et al. 2004). Besides the implementation of these parameters into the geochemical modelling code, in many cases the model also requires the definition of corrosion rate values for oxid and anoxic conditions, together with the predominance of any of these conditions as a function of the available oxygen. Hydrogen, mainly derived from anaerobic steel corrosion present in primary containers and in concrete reinforcement, might also play a role in the retention /migration of redox-sensitive RNs. Under abiotic conditions several metals, such as the epsilon particles (Rh, Pd, Ru) conforming the spent fuel inventory, have been demonstrated to be able to activate H_2(g) (Broczkowski et al. 2005, 2010). The resulting activated H_2(g) is potentially able to supress the spent fuel matrix (UO_2) dissolution process, maintaining uranium under the reduced UO_2 phase (Carbol et al. 2009; Riba et al. 2020; Trummer and Jonsson, 2010). Various microbial metabolisms can be supported by H_2(g) when a suitable terminal electron acceptor is available (ThermoChimie, 2019).

Reduction of sulphate by thermodynamically driven reactions can be neglected due to slow kinetic rate of this process under the low pressure and temperature conditions of the disposal facilities. Sulphate reducing bacteria activity (SRB) is expected to be the only possible pathway for sulphate reduction (Behrends and Bruggeman, 2016; Román-Ross et al. 2015), indirectly promoting the reduction of radionuclides through the formation of Fe(II) and/or sulphide solid phases (Tiedje, 2002). Such disequilibrium reactions can be modelled using different approaches, including decoupling S(+VI) and S(-II) and/or using kinetic models.

Nitrogen, expected to be release by diffusion from the bituminous wastes and high salt level wastes, needs also to be considered as a relevant compound able to impact on the retention / migration of radionuclides (RNs). Bituminous wastes (containing a significant fraction of long-lived, intermediate-level wastes: ILW-LL) are present in wastes like Belgian Eurobitum and French B2 wastes and consist of a mixture of inorganic salts immobilised in a bitumen matrix. The reduction of nitrate could happen i) as an abiotic process being catalysed in steel and corrosion products surfaces with iron or H_2 acting as electron donors (Truche et al. 2013a; Truche et al. 2013b) and ii) as biotic process through microbially-mediated reactions, such as denitrification, being associated to oxidation of dissolved organic matter (Mijnendonckx et al. 2020; Bleyen et al. 2016; 2018).

Organic matter might also have an effect on the redox of the system (C: IV, -IV) (Deniau et al. 2008), being natural organic matter (NOM) well known for its capability to reduce iron phases and numerous redox-active organic and inorganic pollutants (Aeschbacher et al. 2011). Modelling approaches simulating the fate of organics and related changes in redox conditions have to account for the effects of microbial activity on the degradation kinetics, as well as for the spatial and temporal distributions of the chemical species such as terminal electron acceptors, nutrients or toxic substances that control microbial activity.

Furthermore, the review of the State-of-the-Art in redox and kinetics goes beyond developing strategies to implement redox potential in geochemical calculations, it also includes analyzing the uncertainties, challenges, and difficulties in redox measurements and conceptual models. It provides recommendations for future experimental programmes and practical examples for modelling the most relevant redox systems in disposal facilities.

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Buoyancy-Related Groundwater Flows: Comparing the Physics of Hydrothermal and Radwaste Situations

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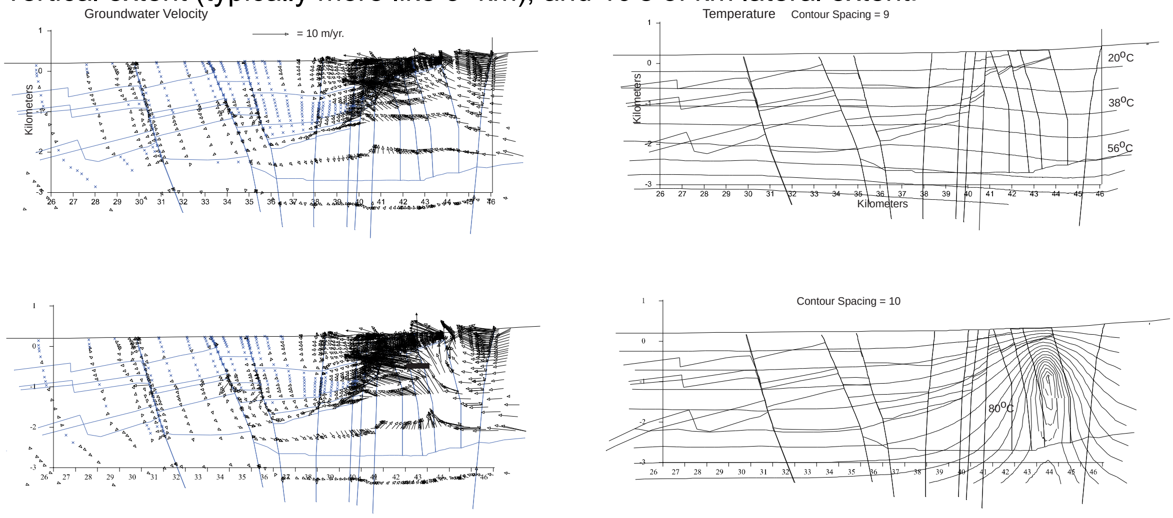
Many sedimentary basins record episodes (both ancient and modern) of anomalously-hot fluid flows that contribute solutes and alter local conditions, resulting in the precipitation of mineral cements containing fluid inclusions that document the characteristics of the fluids. In crystalline rocks, comparable fluid flows, and the resulting deposits of minerals and metals, are commonly associated with faults and similar features that create new and connected void systems. Numerical simulations, of the regional-scale groundwater systems of these varied situations, reveal that such circulations can occur in a steady state condition, without appealing to special circumstances, such as regions of high overpressure. Subsurface temperature data, and accompanying simulations, demonstrate that modern flow systems can alter the local thermal state to temperatures >50C, over lateral distances <3km, greater than what is expected/found for the unperturbed states away from the local flows. An under-appreciated opportunity exists to exploit examples of such flows for geothermal energy extraction, if the thermal anomalies occur in positions shallow enough to suit the engineering constraints.

The physics, which governs the buoyancy-driven flows in natural examples, is equally applicable to situations where radioactive waste could be placed in the subsurface. Numerical simulations of the previously-posed Sellafield site (top row: background case; bottom row: added waste heat in black rectangle), as an example, show that the heat of the waste far exceeds the thermal source perturbation needed to provoke new buoyancy-driven flow. This flow advects heat from depth, substantially altering the temperature distribution, and affecting the path that would be taken by escaped radionuclides. This result contrasts with previous considerations of heat-related convection, which typically employed a small model domain (~O 50m), and which assumed symmetry conditions. Indeed, one of the important findings across the full suite of similar numerical simulations is that asymmetry of the regional groundwater system is an important factor to enable buoyancy-driven responses. The other key finding is that buoyancy-driven flow systems are large, typically involving more than 1km of vertical extent (typically more like 3+km), and 10's of km lateral extent.



It is the slower, low-flux 'outer' fringes of the buoyancy-driven flow system that provide the recharge paths necessary for the system to be sustained. These outer portions of the flow systems operate in rocks with bulk-rock permeabilities <1 micro-Darcy ($<10^{-18}m^{-2}$). That magnitude of bulk permeability is well within the range of upscaled bulk permeabilities for mudrock systems, as found in a long-running consortium project called Caprocks. It is also smaller than the upscaled permeabilities needed in crystalline rocks to explain observed large-scale flow observations. Thus, it appears that there is a need to consider the potential for radioactive-waste-induced alterations of the large-scale hydrogeological responses around a site. It is especially important to assess how such changes may affect the long-range transport of radionuclides that escape the immediate storage locations.

Thermo-Hydro-Mechanical (THM) Design of Finnish Spent Nuclear Fuel Repository

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This paper presents modelling of long term performance of engineered barrier systems (EBS) in crystalline host rock in terms of coupled thermal–hydraulic–mechanical (THM) processes, in one case considering also the impact of salinity linked with geochemistry. This study has been used as a supporting document for the Safety Case in the process of the Operating License Application for the Olkiluoto spent nuclear fuel repository in Finland.

The disposal design chosen is the KBS-3V which consists of the emplacement of the canisters in vertical deposition holes (Fig. 1a) surrounded with the EBS. One of the alternatives in the EBS design, compacted blocks of Wyoming bentonite surrounding with pillow pellets manufactured with the same material (Fig. 1b) are the buffer material. Bulgarian and/or Italian granular filling (GraFI) materials are the backfilling material in the deposition tunnels. Barcelona Basic Model (BBM) is considered for modeling the geomechanical behavior of compacted buffer blocks and GraFI materials filling the deposition tunnels, while for pellets Barcelona Expansive Model (BExM) considering double structure (macro-micro porosity) has been used.

A laboratory testing campaign (thermal conductivity, water retention curve, oedometer and infiltration tests) has been carried out in order to fit THM model parameters of the corresponding materials.

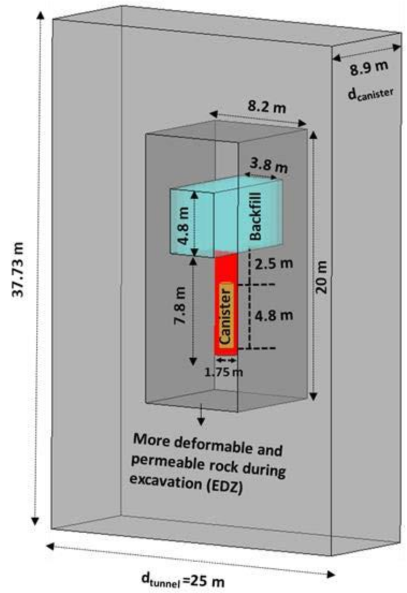
Model-data uncertainties, challenges and followed methodology have been discussed in terms of modelling capabilities. 3D THM simulation of an individual deposition hole (canister, notch and buffer materials) drilled into a deposition tunnel (backfill material) has been implemented in CODE_BRIGHT as a Finite Element Method (FEM) program. Previous 2D – THM calculations [1 and 2] have been considered as reference works (TH boundary conditions, decay function for canister power, tunnel and canister spacing etc.) for further 3D calculations.

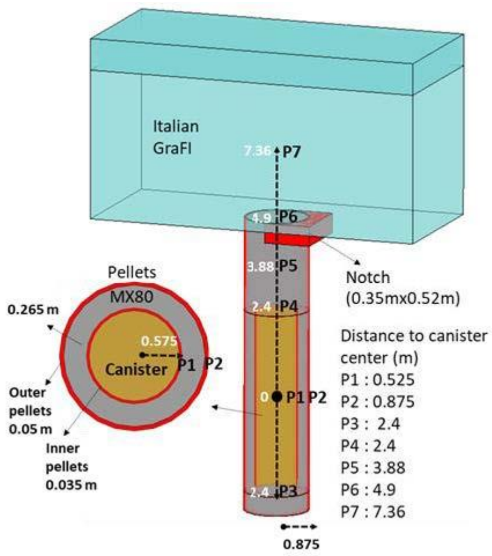
This study present results associated with THM performance of EBS such as peak temperature; time required to reach full saturation in buffer and backfill, development of swelling pressure (Fig. 1c) in buffer and backfill and consequently deformations in buffer and backfill domain.

A sensitivity analyses plan has been followed in order to deal with various factors affecting long-term THM performance of the EBS. In the sensitivity analyses, buffer and backfill design alternatives (different filling material alternative), geological conditions (saline water, rock permeability and heterogeneous rock) and numerical simulation options (different numerical model options, issues related to geometry and meshing) have been investigated.

The performance targets and design specifications set for buffer and backfill have been discussed. The paper concludes with a summary how the design (geometry, initial conditions, boundary conditions and buffer and backfill materials) meets the performance targets set for buffer, backfill and host rock.

Keywords: nuclear waste repository design, engineered barrier system (EBS), THM coupled processes, BBM, double structure model, CODE_BRIGHT





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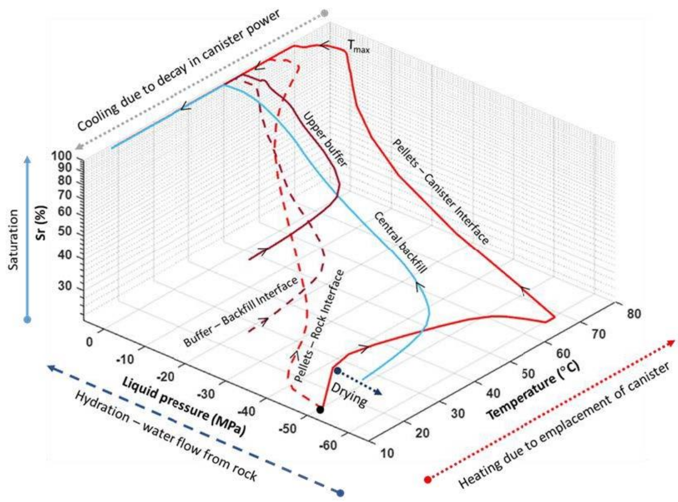

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Figure 1. Geometrical details for the model (a), considered locations in the model geometry (b) and peff-liquid pressure-temperature path for the corresponding locations.

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Nano-scale imaging and modelling of gas transport in clay-rich mudstones

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Geological disposal of radioactive wastes into subsurface formation is a storage option favoured by many countries. Clay-rich mudstones are often considered as a suitable host rock formation for placing geo-disposal facilities (GDF) due to their low permeability and high sealing ability. In these systems, hydrogen gas may form due to the anoxic corrosion and degradation of steel canisters used in the underground radioactive waste repositories, resulting in the accumulation of pressure leading to rock deformation, gas migration and potential gas and other solute leakage [1]. Therefore, an understanding of hydrogen-sealing capacity of mudstones, specifically the examination of hydrogen gas transport behaviour within the clay nanopores which largely constitute the mudstone rock matrixes, is important in the development of safety cases in GDF settings.

Current transport models characterizing the geological transportation of subsurface fluids are not sufficient to understand the complex transport pathways and mechanisms in clay-rich rocks at nanoscale, owing to the lack of nano-scale quantitative measurement and images relating to the study of gas transport phenomenon. With recognition that 3D micro- and nano-scale X-ray computed tomography (Micro- and Nano-CT) and Focused Ion Beam Scanning Electron Microscopy (FIB-SEM) commonly used for pore network modelling are insufficient to describe the clay-rich mudstones of nanometric pore sizes, Transmission Electron Microscope (TEM) can be adapted to provide further microstructural information for its high magnification [2]. This research will thus implement TEM microscopy in addition to the micro-scale characterization methods to provide a more systematic characterization of clay-rich mudstones, supplementing realistic host rock information for future analytical works.

Core samples extracted from the Lias mudstone formation deposited in Eastern England are adapted for common host rock representations [3] in this study, where the characterization workflow was then performed from micro- to nanoscales. Mineral contents and depositions were investigated with SEM-EDS and XRD, Pore size distribution, geometry and networks were examined through a combination of nitrogen adsorption, SEM and STEM imaging, as well as Micro- and Nano-CT, while the crystalline lattice structures of the clay particles were analysed using TEM imaging and diffraction.

It has been unveiled that the clay-rich mudstone sample consists of solid crystals including quartz, calcite and pyrite, while kaolinite, illite and smectite groups constitute the clay matrix. A complex porous system consisting micro-, meso- and macropores was obtained from the mudstone, in which clay interlayer micropores of diameters below 2 nm dominate the pore network, hence were further quantified with relation to each specific clay groups by their associated lattice spacings. Therefore, this study was able to identify how various mineral components and clay groups contribute to the rock microstructure, while providing information on estimations to the gas flow behaviour within the rock matrix in correlation to existing flow channels and pathways, as well as raising more realistic propositions on molecular dynamic modelling set-up conditions, and therefore giving insights on the gas trapping potential onto the clay nano-porous surfaces by considering the gas-fluid-rock affinity and their corresponding adsorption capacity. This research provided unique images and quantifications for clay-rich mudstone characterization, thus correlated the findings to mechanistic gas transport studies and yielded insights to GDF designs, contributing to the new era of our energy future.

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POSTER ABSTRACTS

Observing and quantifying deformation behaviours in halite for applications in compressed air energy storage (CAES)

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Halite formations are of interest in relation to the disposal of radioactive waste, both historically as a potential host formation and in the UK as a lithology present across a range of scales within the Mercia Mudstone Group. Several notable properties are beneficial to waste storage, namely its low overall permeability, ductility and self-sealing properties. In addition, it has a high thermal conductivity, relative to other sedimentary formations, with the potential to promote heat transfer within a Geological Disposal Facility (GDF). In the UK, halite members are present within the Mercia Mudstone Group, which is of interest as potential host formation for a GDF. However, high salinity environments can lead to enhanced corrosion of repository infrastructure and impact barrier performance. As part of an EPSRC-funded project (SAFE-CAES), the British Geological Survey has been examining the thermo-hydro-mechanical behaviour of UK halites in the context of Compressed Air Energy Storage. Learning from this study is of direct relevant to potential UK host rock formations in which halite members are present. We present findings from bespoke experiments conducted in the Transport Properties and Research Laboratories lab at the BGS investigating the deformation behaviour of halite. Testing was conducted under both isotropic and triaxial conditions, to examine the impact of temperature and the deformation of the samples under different effective stress conditions.

In both test geometries, halite samples were manufactured by machine-lathing to produce cylindrical samples of the required diameter. In each sample a hole was drilled part way through the core, with hole diameters ranging from 10-22 mm. During testing this hole was pressurised with compressed air. Samples were scanned using Computerised Tomography (CT) in the BGS's state-of-the-art Core Scanning Facility, both before and after testing. In the isotropic tests, CT imaging of each core was performed weekly to assess the impact of varying temperature on the volume of the drilled hole. Post processing of CT data was undertaken for all samples using PerGeos to assess deformation of the drill holes as a function of pressure and temperature.

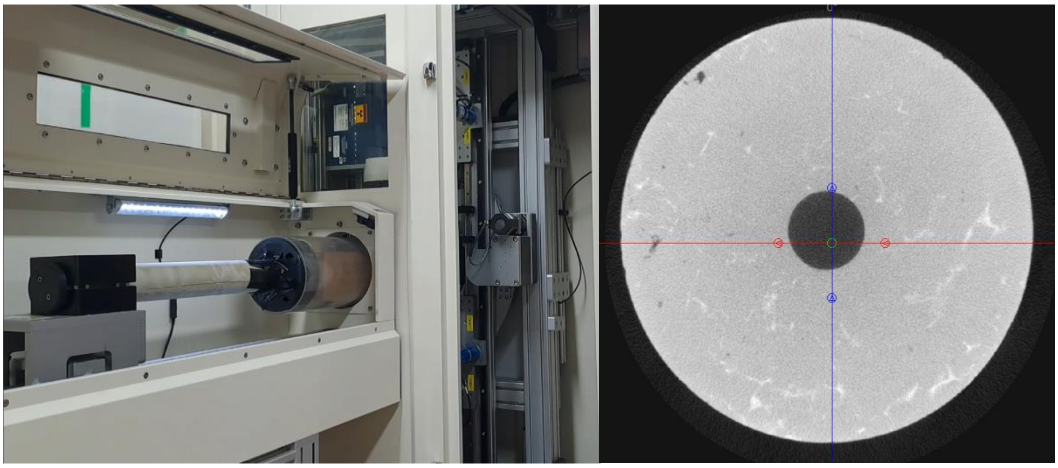

Figure 1: Left, the Rotating X-ray CT hosted at the Core Scanning Facility, managed by Dr Magret Damaschke and Dr Elisabeth Steer. Right, an example of a halite sample CT image with the internal void space visible in the centre. Light patches are clay inclusions whilst other dark inclusions are internal natural voids within the salt.

For isotropic tests, samples were placed between two stainless steel platens, with a porous filter located between the upper platen and the end of the sample containing the hole. The platens and sample were isolated from the confining fluid of the pressure vessel using heat shrink Teflon, Figure 2. For isotropic tests, confining and gas pressures were fixed at 31.2 MPa and 25.0 MPa respectively, the latter equivalent to 80% of lithostatic pressure at the Boulby Mine. Temperature was then varied between 35°C and 120°C, in a series of steps, with CT imaging performed between each step. For triaxial tests (Figure 2), samples were placed within a flexible Hoek sleeve and fitted with 9 LVDT radial strain sensors, which could then be used to track the spatial development of deformation during testing. Tests were performed under ambient temperatures (circa 20°C) with axial and radial stresses held constant at circa 31.3 and 30.6 MPa respectively. The internal gas pressure was initially fixed at 80% of lithostatic pressure, and then decremented in a series of steps while deformation

was observed.

Figure 2: Left: the isotropic rig used for thermal testing. The halite sample sits within an isotropic pressure vessel (centre). Right: the triaxial cell - the radial sensors protude from the central housing.

Deformation rates were relatively slow for holes drilled with diameters of 10 and 16 mm. In the triaxial experiments, deformation was directly measured and found to increase as gas pressure within the hole decreased. In one triaxial test, performed on the Gateway halite, gas pressure unexpectedly decreased to atmospheric pressure. While this led to a significant increase in deformation, the sample remained structurally intact, suggesting the halite was relatively competent. Similarly, isotropic tests performed on the Boulby halite at temperatures up to 95°C, also demonstrated minimal volume change in rock samples with hole diameters less than 16mm. CT imaging also suggests that internal fractures (the initial origin of which remains unclear) began to close as temperature increased, and as loading pressures were sustained. Based on the limited amount of data available, these features do not appear to act as foci for deformation. The data also shows that halite on heating exhibits self-sealing behaviour, which will be beneficial in the excavation damage zone proximal to heat generating radiogenic waste.

Initial findings from this study highlight the importance of understanding the deformation behaviour of halite, which will help to provide important information on the mechanical behaviour of UK halites. Further experimental assessment of the stability of these materials, in both primary halite host rocks and halite members within other low permeability formations such as the Mercia Mudstone Group will help inform considerations relating to the construction and evolution of a UK GDF.

The Triassic Mercia Mudstone Group as a host rock for radioactive waste: insights from a continuous core succession in North Yorkshire

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The safe disposal of radioactive waste is an unresolved issue in the UK. As in many other countries, the search for an appropriate Geological Disposal Facility (GDF) includes considering Mesozoic mudstones as potential low-strength sedimentary host rocks. The Middle to Upper Triassic Mercia Mudstone Group and its offshore continuation, the Haisborough Group, combine two lithologies thought to have favourable host rock properties – mudstones and evaporites – and are a focus of current Community Partnership assessments in west Cumbria. However, these units are understudied, due to generally poor outcrop conditions and the dearth of core materials.

CASP had the chance to sample an onshore core from the Cleveland Basin north of Scarborough, North Yorkshire, UK, which offers a unique opportunity to study a continuous, near 300-m-thick succession of Middle to Upper Triassic strata encompassing the entire Mercia Mudstone Group. We are taking a multidisciplinary approach to the cored succession to assess its stratigraphy, composition and geomechanical behaviour. While primarily collected in the context of Geological Carbon Storage (GCS), the same data and properties, including porosity, permeability, clay content, rock strength and stratigraphic variability, are relevant to GDF assessment.

A total of 64 more or less evenly spaced core samples were taken from the entire succession, also accounting for facies heterogeneity. To best describe the composition of these rocks, we combine sedimentary logging and facies analysis, hand-held X-ray fluorescence (XRF) analysis, quantitative X-ray diffraction (QXRD) analysis, optical petrography and scanning electron microscope energy dispersive spectroscopy (SEM-EDS). Porosity-permeability and mercury injection capillary pressure (MICP) analyses are being carried out to assess the suitability of these strata as a seal. In addition, geomechanical analytical results from fresh core are available. These data will be integrated with palynostratigraphy from more than 130 samples and a comprehensive suite of wireline log data, to facilitate robust chronostratigraphic correlation. Select core and cuttings samples from offshore wells in the UK and Dutch sectors of the Southern North Sea are also being analysed using similar methods to address lateral variability. A sister project of CASP extends this dataset into the overlying marine Lower Jurassic Redcar Mudstone Formation of the Cleveland Basin, and may provide further insights relevant to GDF assessment, particularly in Lincolnshire.

Logging and facies analysis identified a conformal but distinct boundary between the Bunter Sandstone Formation and the overlying Mercia Mudstone Group. Given the near-coastal location of the well and the lack of a formal subdivision of the Mercia Mudstone Group in the Cleveland Basin, a preliminary lithostratigraphic framework is being constructed based on the Haisborough Group, focusing on sediment textures and the abundances of halite, anhydrite and dolomite cement for subdivision. Throughout the succession, optical petrographic, SEM-EDS and QXRD analyses identify anhydrite, clay minerals, dolomite, quartz and feldspar as common mineral components at varying proportions. Halite is largely confined to the Röt Halite Member of the Dowsing Formation, where it is pervasive. Elsewhere, compositional variation is mostly driven by the abundance of anhydrite, which occurs either finely dispersed, or concentrated in streaks, veins or nodules, often also healing fractures. QXRD analysis further records widely varying clay contents (10 to 65%), mainly illite + smectite, but also significant proportions of muscovite, chlorite and corrensite. Porosity-permeability and MICP analyses yield encouraging results with regard to validating the suitability of the Mercia Mudstone Group as a seal.

The influence of depositional and diagenetic heterogeneity on fracture distributions in the Mercia Mudstone Group

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The Mercia Mudstone Group (MMG) is currently of great interest as it may host the UK’s geological disposal facility (GDF) for higher activity radioactive waste; it will also serve as the top seal to sandstone reservoirs for both carbon dioxide and hydrogen storage sites in the Irish Sea and North Sea and it may host engineered salt caverns for hydrogen storage. A significant challenge is that the MMG is inherently heterogeneous. Here we describe a study that is gathering outcrop, quarry, borehole and log data on the lithological, depositional, and diagenetic heterogeneities of the MMG to gain an insight into their influence on fracturing and, specifically, fracture type, density and distribution. Until fractures can be ruled out as local conduits for fluid flow, it must be assumed that they will lead to significantly increased secondary, and strongly heterogeneous, permeability. A comprehensive dataset is being collected to understand the heterogeneity of fracture type, distribution, and density within the MMG. Fractures will be logged using scanlines in both borehole core and outcrop and quarry exposures. A variety of information about fracture populations will be gathered including spacing, density, aperture and cementation, and related to sedimentary and diagenetic logs to establish links between lithology, diagenesis and fractures. In this study, sedimentary and structural logs have been produced of the Cropwell Bridge borehole (East Midlands Shelf) and of field exposures in Watchet (Somerset Basin), Sidmouth (Wessex Basin) and northwest England. Sedimentological and structural data will allow us to develop our understanding of the types and ranges of structural and lithological heterogeneity in the MMG. Numerous lithologies have been identified, each characterised by a wide range of depositional and diagenetic textures and mineral constitutions. The potential for self-sealing of lithology-dependent fractures in the MMG is poorly understood and is a special focus of this research. The output from this work will inform discrete fracture network models, which will be key components of a geospatial site descriptive model for the GDF if it is to be hosted in the MMG.

EVOLUTION OF BENTONITE PORE WATER CHEMISTRY UPON RESATURATION WITH SALINE GROUNDWATER

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Bentonite, a montmorillonite clay-rich material, is an important engineering material used in geological disposal facilities (GDFs) for radioactive waste, due to its exceptional swelling properties and low hydraulic conductivity in the presence of groundwater. For example, it is used in sealing site investigation boreholes, backfilling underground accessway and as a local backfill/buffer around high heat generating waste containers. However, limited research has examined how the pore-water chemistry of bentonite evolves when interacting with typical UK groundwaters, which in potential siting areas tend to be hypersaline (>seawater concentration) (Smedley et. al., 2022) at repository depths of 200-1000m. Elevated salinity can reduce the swelling capacity and increase the hydraulic conductivity of bentonite barriers.

This study investigated the evolution of bentonite porewater chemistry when interacting with synthetic hypersaline groundwaters. These groundwaters, represents those expected in geological formations identified in current potential UK GDF siting locations. The focus was on bentonite samples obtained from a decommissioned 'mock-up' borehole sealing experiment, undertaken by the UK GDF implementer, Nuclear Waste Services. The sample comprised 2x 100mm long sections of plexiglass tube containing a mixture of 50% Pel-Plug (Western) and 50% almond MX80 (Wyoming) sodium bentonites, which had been saturated for 312 days at a dry density of 819kg/m^3. The bentonite samples were homogenized by mixing thoroughly before being used in the swelling, and leaching experiments in this study. Free-swelling tests, and aqueous leaching, was conducted for a range of groundwater chemistries (including basinal brine/formation waters; halite contacted brines and brine-meteoric water mixtures). Bentonite swelling decreased as groundwater salinity increased, likely due to osmotic effects limiting montmorillonite hydration (Figure 1). Cation exchange occurred with increased sodium and decreased calcium in porewaters after bentonite interaction. This agrees with exchange of Na^+ from groundwater with Ca^{2+} occupying bentonite interlayer sites (Appelo and Postma, 2005; Komine 2004). Chloride concentrations correlated with starting groundwater compositions, behaving conservatively and possibly related to anion exclusion from montmorillonite surfaces. Low aluminium release suggested limited montmorillonite dissolution over the experimental timeframe.
The findings have implications regarding compacted bentonite performance when exposed to UK groundwater chemistries. Reduced swelling capacity in hypersaline conditions needs to be considered when setting requirements for long-term sealing efficiency and mechanical stability of bentonite barriers. Cation exchange will also alter key properties dependent on porewater composition like swelling pressure. Further experimental and modelling work is required to explore the impacts of these groundwaters on the development of swelling pressure under appropriate boundary conditions.

Table 1: Showing total dissolved solids (TDS) of Synthetic Groundwater

Sample Name	Mercia Mudstone, high salinity (mg/L)	Mercia Mudstone, low salinity (mg/L)	Ancholme group, high salinity (mg/L)	Ancholme group, low salinity (mg/L)	Opalinus Clay (mg/L)
TDS	318,983	189,359	36,116	5,163	20,207

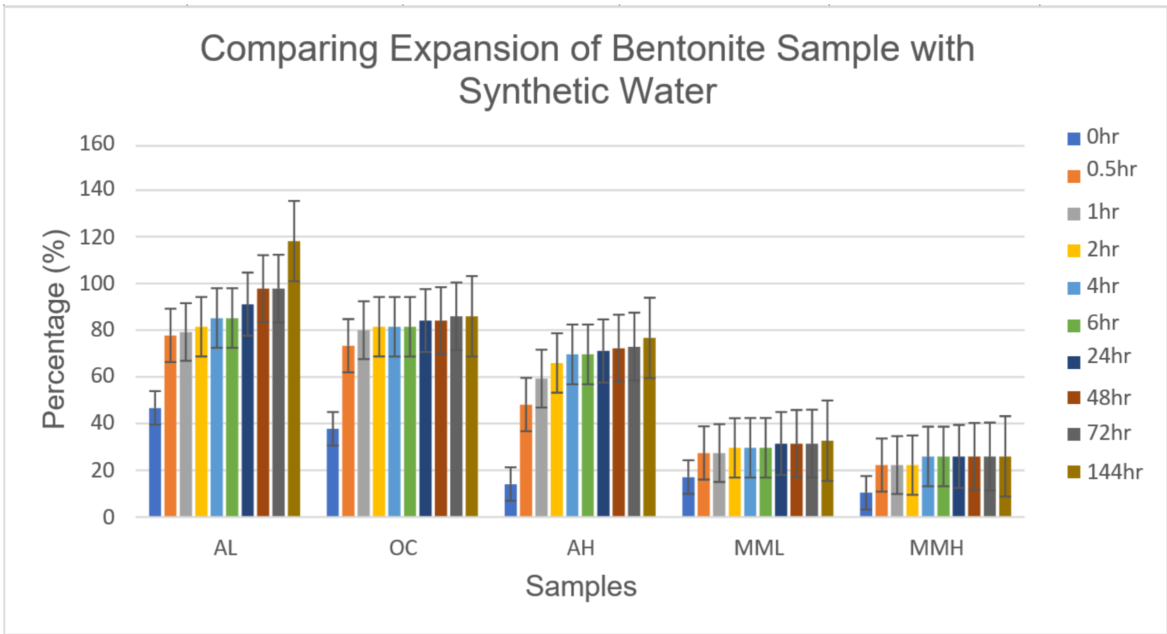

Figure 1: Chart Comparing Percentage Rise of Bentonite Samples when added to Synthetic Groundwater for The Period of 144 Hours. (Ancholme Group Low Salinity (AL), Ancholme Group High Salinity (AH), Mercia Mudstone Group High Salinity (MMH), Mercia Mudstone Group Low Salinity (MML), and Opalinus Clay (OC)).

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Adapting disposal concepts to reflect emerging UK geological environments

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Poster presentation

In the absence of a specific site, the UK has based its illustrative geological disposal concepts for higher activity radioactive wastes on three generic host rock classifications. These are Lower Strength Sedimentary Rocks (LSSRs), such as clay, Higher Strength Rocks (HSRs) such as granite, and evaporites such as halite. These generic classifications have been informed by more advanced disposal programmes within the international community.

In December 2018 and January 2019, the UK and Welsh governments published the *Working with Communities* policy, which outlined the approach for locating a geological disposal facility for higher activity wastes. This enshrined a community consent-based approach and the requirement that Nuclear Waste Services (previously Radioactive Waste Management), as the GDF implementor, ensures safety, security and environmental protection throughout the lifetime of the programme. To date, there are three Community Partnerships working with NWS to determine whether hosting a facility is right for them. These are Mid Copeland and South Copeland in Cumbria and Theddlethorpe in Lincolnshire. As of January 2024, a new Working Group has formed in South Holderness, East Riding of Yorkshire. These communities bring with them their own unique geologies, and NWS will need to adapt the illustrative disposal concepts or develop new disposal concepts that are compatible with the site-specific environment.

The Mercia Mudstone Group (MMG) is the potential host rock found in relation to the Mid and South Copeland Community Partnerships. This is classified as a LSSR; it is comprised of a mixture of mudstone and halite and its properties are likely to span all three generic rock classifications. Therefore, the current illustrative LSSR concepts are not optimised for the MMG. One key consideration is the impact of the hypersaline groundwater (salinity >> seawater concentrations) on the performance of the GDF engineered barriers. For example, bentonite is proposed in the LSSR illustrative concepts as a buffer/local backfill for high heat generating wastes and as the sealing component for vault plugs and seals and in accessways. The ability of bentonite to swell is controlled by the chemical composition of the groundwater, whereby higher salinities reduce the swelling capacity of bentonite. NWS has reviewed the existing literature on this topic and has commenced a programme of work to understand the performance of bentonite in hypersaline environments. The aim of this poster is to provide an overview of this ongoing programme of work.

Using analogue tests to observe fundamentals of gas flow in clay-rich rocks and barrier systems

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Analogue tests allow direct observation of pathway growth and are quick to perform, meaning that a comprehensive study with as many as 100 tests can be performed as quickly as a single test in competent rock. With that in mind, an experimental programme of around 50 experiments was devised as part of the EU EURAD-GAS project to answer specific research questions: 1) Do we see similar behaviour (gas entry pressure, pathway network etc) for five repeat tests? 2) Do we see agreement between different clay types? 3) Do we see differences in behaviour for variations in moisture content? 4) Do we see evidence of self-sealing of gas pathways? 5) What happens if gas supply stops? 5) Do we see any change in behaviour with pressurisation rate? 6) Do we see any change in behaviour over a range of sand/bentonite mixes? 7) Do we see any changes in behaviour over a range of normal loads? 8) Do we see episodic flow?

A bespoke apparatus has been constructed at the BGS. A ~1mm thick clay paste made from ball-milled rock is viewed through a 150mm diameter glass window. Normal load is imposed by bolts acting upon a rigid steel collar giving a normal load of around 1 MPa. At the outer edge of the sample is a porous filter, which allows gas and water to drain from the sample. During a two-hour long gas injection test, the viewing window was photographed every 3 seconds. In the current study, gas flow properties were examined in Callovo-Oxfordian Claystone from France, Opalinus Clay from Switzerland, Boom Clay from Belgium/Netherlands, and Mx-80 bentonite.

All experiments showed similar pathway formation. In all four pastes, dilatant pathways formed with a stochastic distribution. The pathways seen in Boom Clay tended to be much broader than those seen in Callovo-Oxfordian claystone and Opalinus Clay. In all four paste types, pathways branched and created a dendritic distribution of pathways. The end distribution was dictated by the initial formation of pathways and how many populations of pathways formed close to the injection point. Comparison of each test showed that no significant difference was seen in the physics creating pathways in clay paste. It is therefore concluded that all four clay types showed the formation of a dendritic pattern of pathways from the central injection point with a stochastic distribution. Early pathway formation dictated the end distribution of pathways.

Close examination of pathways showed a halo feature around some pathways. The compression of the clay near the injection port resulted in a lightening of the greyscale, meaning that compressed clay lightened in greyscale. Therefore, the halo showed that the wall of the clay either side of the pathways compressed to accommodate the dilating pathway. The halo was around five times the width of the pathway on both sides. This confirms the conceptual model of dilatant pathway migration with the compression of pathway walls. This is further confirmed by observing the closure of pathways. As gas pressure reduced, some pathways elastically closed completely, leaving a faint trace of the pathway as a darker grey lineation. Closure of the pathways also resulted in the opening of other features, such as gas bubbles or pathways. This demonstrated that the compressed clay either side of the feature pathway was elastically opened, and once pressure reduced the elasticity resulted in the closure of the pathway. Some pathways remain opened, but this is likely to result from friction between the clay and/or steel baseplate.

Experiments were initially conducted in each clay type at different water content to determine the ideal water content. In Boom Clay, the geometry and velocity of pathway formation was seen to be strongly influenced by water content. For a high content of 42%, thin pathways formed that took around 18 minutes to reach breakthrough. At a lower water content of 37% it took around 15 seconds to reach breakthrough and the width of pathways was very broad compared with those that formed at a water content of 42%. At the lowest water content of 32%, it took less than 6 seconds to reach breakthrough and very broad pathways formed. Therefore, water content controls the size of the pathways and the velocity of pathway propagation. At lower water content, the paste behaved more energetically, while at higher water content it behaved as expected with slow propagation of dilatant pathways. At a higher water content there was more closure of the pathways once gas pressure had been relieved.

Important observations of self-sealing was seen in two experiments. Midway through the pathway propagation phase, gas pressure was relieved as a pathway reached the outside of the sample. This resulted in the elastic closure of pathways, especially at the centre of the sample. A secondary set of pathways then formed which did not match the primary set, as shown in Figure 1. As the pathways propagated, the clay ahead of the pathway compressed, resulting in further closure of the existing pathways. As a result, some of the secondary pathways cut directly across the existing pathways, meaning that the primary pathways had self-healed and did not represent a mechanical weakness for the propagating pathways to exploit. The time-lapse video of the experiment suggests that the primary set of pathways played no role in the distribution of the secondary set, and the latter formed as if the former had never formed. However, at the periphery of the viewed area, some of the secondary paths appear to have connected with the primary set.

The use of carefully designed analogue tests using clay pastes have confirmed key aspects of the dilatant pathway gas flow mechanism. These were previously inferred from interpretation of experiments on competent rock samples where direct observation was not possible.

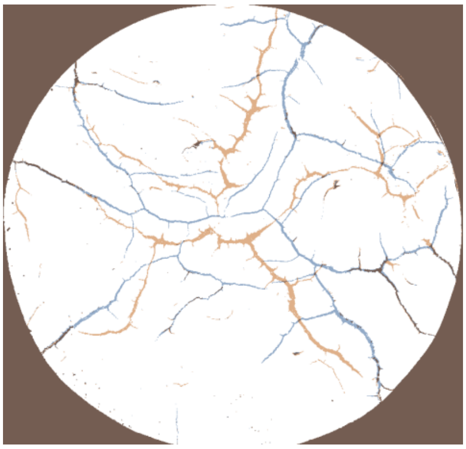

Figure 1 – Comparison of pathway population 1(blue) and 2 (green) showing evidence of self-sealing in Callovo-Oxfordian claystone.

Controls on the Gas Permeability of the Triassic Mercia Mudstone Group, UK

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Lower-strength sedimentary rocks (i.e., mudstones and evaporites) are of general interest for geological storage of nuclear waste due to their useful properties, including low hydraulic conductivity, and fracture self-sealing potential (Zhang, 2018). The Mercia Mudstone Group (MMG) has been identified as a potential host rock for the UK's Geological Disposal Facility in northwest England. Consequently, detailed fluid transport properties of this host rock must be understood before site selection can be finalised.

One issue with the Mercia Mudstone Group is its heterogeneity, on a variety of scales, from millimetre to basin scale. This heterogeneity arises due to the range of depositional environments and burial depths in different regions. Samples with differing depositional and diagenetic features will behave differently when stress is applied; for example, pressure sensitivity and directional dependence of permeability vary extensively between different samples. This study collates data from different analytical techniques including light optical and SEM examination, XRD analysis, mercury intrusion and permeability measurements. This combination of methods is crucial to understand the main controls of permeability, and how the host rock will behave under subsurface conditions, especially those influenced by the storage of radioactive waste.

Previous work at the University of Liverpool has shown low permeability of the Mercia Mudstone Group, controlled by primary depositional features and diagenesis (Armitage et al., 2013, Armitage et al., 2016). Permeability has not yet been extensively reported for a complete succession of the MMG; the principal controls on fluid migration have not yet been established. A new suite of samples from the Cropwell Bishop Borehole, Nottinghamshire, were obtained from core stored by the British Geological Survey in Keyworth. These samples are from present day depths of 12.3 to 184.5 m. This borehole intersects the Tarporley, Sidmouth, Arden, and Branscombe Formations within the MMG. Core ranges from mudstones, silty mudstone, and sandstone with an abundance of gypsum in the form of fibrous veins and chicken wire textures. Reduction spots and pedogenic fabrics are common throughout the Cropwell Bishop core. Colour ranges from chocolate brown, in the muddier beds, to grey green in the siltier beds. Analyses using light optics and SEM have shown various detrital minerals predominantly consisting of quartz, K-feldspar and illite. Diagenetic pore filling minerals are dominated by gypsum, calcite, and dolomite. Where clay minerals are observed within pore spaces, diagenetic pore-filling minerals tend to be absent. Measured porosity of samples ranges from 3.0 to 13.3 %. Pore throat diameter ranges from 12 to 121 nm from the Sidmouth Formation, across a 114.2 m depth range. Establishing controls on porosity is important as porosity influences permeability. Measured permeability varies from 10^{-21} to 10^{-17} m^2 (approximately 10^{-6} to 10^{-2} mD) across the range of different lithologies. For one single sample, permeability ranges across two orders of magnitude when increasing effective stress, because of mineralogical and depositional features.

The ongoing work will deliver a unique dataset on the permeability stratigraphy, and its controls, for all formations within the MMG. This will lead to a better understanding of the fluid flow properties of a possible Geological Disposal Facility sited within the MMG.

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Characterisation of Mercia Mudstone Containing Mineralised Fractures

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The Mercia Mudstone is a group of mudrock geological strata that spreads the English territory. This formation could be a host for nuclear geological disposal facilities (GDFs) in the UK because of its low permeability and self-healing nature. Field observations demonstrate that the Mercia Mudstone often contains mineralised fractures (veins) - factures sealed by minerals, e.g., halite, and gypsum - however, it is unclear whether the inclusion of the veins could compromise the self-healing capability of the rock. We will contribute to understanding the question in this study. We collect Mercia Mudstone core samples with veins from the British Geological Survey and characterise the texture and mineralogy of the samples. We use X-ray CT to characterise the 3D structural geometry of the veins non-destructively and investigate the evolution of micro-structures (e.g., pore, vein structures) under subsurface environments. The complexity of vein structures partially arises from the intrinsic heterogeneity of mineral phases and their changes over engineering and geological timescales. We also believe that the lab-based observation could provide invaluable, unique input data for modelling the long-term dynamic behaviour of veined clay formation. It is also worth further looking at the dissolution and recrystallization of the vein-filling minerals and their implications for the permeability evolution of the host rock. We anticipate this work could inform the site sitting and safety design of GDF.

Excavation Disturbance Zone Evolution in UK Jurassic and Triassic Mudrocks – Implications on fluid flow in a nuclear waste repository

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The UK's Geological Disposal Facility (GDF) is being planned for permanent isolation and containment of higher-activity radioactive waste in the deep subsurface. A multibarrier system is required to fulfil the objectives of the GDF, comprising a combination of natural and engineered barriers, one of which being the host rock that waste is emplaced within. During the construction, operation, closure and post-closure of a GDF, the removal of rock materials would lead to stress re-distribution especially in areas proximal to the zone of excavation. This may lead to the development of faults and fractures, impacting rock properties such as permeability and hydraulic conductivity (Bossart et.al, 2000)

This study aims to investigate the impact of the excavation disturbance on the UK's Jurassic and Triassic mudstones under consideration for a GDF, broadly consisting of variable sequences of calcareous clays, mudstones and evaporites (Figure 1). The main clay minerals are usually illite, chlorite and smectite (BGS, 2002). These argillaceous rock group, largely characterised by a high portion of clay minerals, are broadly similar in mineralogical composition to the Callovo-Oxfordian formation and the Opalinus Clay used in EDZ studies of GDF at the Bure and Mont Terri Underground Research Laboratories respectively (OECD, 2010). Previous studies conducted at the Mont Terri and Bure URLs have shown that the type and structure of the clay minerals in the host rock play a crucial role in the mechanical, hydromechanical, and geochemical behaviour of the EDZ at both micro and macro scales.

Hydrogeological investigation of argillaceous formation such as the Opalinus Clay has shown hydraulic transmittivities of higher magnitude in the inner zone of the EDZ has compared with the undisturbed host rock; implying a faster pathway for the migration of radionuclides. Thus in exploring the behaviour of rock deformation and fluid migration and the implication on fluid flow, the study will conduct a multiscale characterisation of the nature and extent of the evolution of the EDZ propagation in potential GDF host rocks.

The 4-year work plan, which is currently at the initial data gathering stage, includes the identification of live sites of EDZ creation, such as mines or road cuttings intersecting the Jurassic Clay and Mercia Mudstone lithologies, and an experimental programme of hydromechanical testing. A macro-scale study of the host rock exposures using remote sensing will be undertaken to map deformation and gather data to resolve strain distribution. Repeat measurements will be made at defined time intervals or as site accessibility permits to assess the evolution of macroscale deformation.

Experiments will investigate the impact of stress redistribution on the microstructural deformation and the alteration of rock properties, capturing the variable conditions anticipated in the EDZ. Hydraulic testing will examine the impact of bedding and fracture orientation on fluid flow and assess the self-sealing capacity of the rock types over experimental time frame. Tests will utilise representative synthetic groundwater and, potentially, cement conditioned pore water.

Figure 7. An exposure of the Mercia Mudstone at Watchet beach west, Somerset, UK

A solid-phase analysis will be conducted on rock samples pre-experiment and post-experiment to determine the internal micro-structure using SEM-EDX, characterise pore size distribution, pore volume and evaluate changes to bulk porosity using Mercury Intrusion Porosimetry (MIP) and gas adsorption techniques. The study will explore possible deformation-induced microstructural changes using the Anisotropy of Magnetic Susceptibility (AMS) technique. Information about the orientation of the distribution of magnetic minerals can be obtained by injecting ferrofluid in the rock and measuring the magnetic field to a high precision (e.g. Borradaile and Jackson, 2010). AMS measurements will be taken pre- and post-impregnation of the rock sample to better understand the rock fabric, pore network, pore connectivity and ultimately characterise the rock deformation and monitor change in structure. Results will be validated using non-magnetic analyses such as SEM-XRD. Post-mortem analysis sampling and analysis to evaluate fracture mineralisation (if any) and their impact on fluid flow will be conducted. Data analysis focusing on establishing the multiscale deformation processes and its implication on fluid flow will be done to aid the production of a 4-D simplified EDZ conceptual model.

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Conceptual workflow for coupled hydro-chemical-mechanical analysis of mudstone based fault zones

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One of the requirements for a Geological Disposal Facility is that it needs to contain radionuclides away from the surface environment whilst they are still harmful. For some radionuclides this can be many tens of thousands of years. The containment function of a geological setting is affected by the presence of fault-fracture systems, which can create pathways for the migration of radionuclides carried by gas and water.

One of the potential host rocks is the Mercia Mudrock Group (MMG); and the conduit versus barrier behaviour for fluid-flow of fault-fracture systems therein is uncertain, due to cascading feedbacks on chemical and mechanical properties, especially at shallow depth. Characterisation of the inshore, deep, saline setting considered for the GDF is complicated by the fault-fracture system architecture and the complex mechanical stratigraphy of the interbedded mudrock and evaporites of the MMG. A key element of this characterisation process will be to demonstrate an understanding of the fracture hosted (single and two phase) fluid flow and solute transport process. As such, a key requirement is the understanding of tools, processes and validation approaches involved with numerical representation of fault- fracture systems in the MMG, including the forward prediction of radionuclide mobility. Key for this prediction is to understand hydro-chemical-mechanical processes associated with faults and fractures. This research aims at improving this understanding.

Fault zone cementation and structure in mudstones in general and MMG more specifically have been under researched over the decades, for multiple reasons, including difficulties in sampling and lack of interest in caprock behaviour prior to subsurface-gas-storage infrastructure projects.

This poster proposes a workflow and hypotheses for the assessment of coupled processes and their impact on permeability, within the context of gas-leakage risk from subsurface nuclear waste storage in the Mercia Mudstone Group. This involves chemo-mechanical characterisation, assessing the relation with changing permeability. Laboratory experiments and field studies of fractures and their associated mineral fill will be fundamental to this

research.

Manufacturing and geotechnical characterisation of synthetic samples for engineered barrier system in radioactive waste repositories

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The engineered barrier system (EBS) is an essential component of any radioactive waste repository, regardless of concept or country. The EBS has been designed to delay or even prohibit the release of radionuclides from a waste canister into the surrounding host rock or geosphere. In many concepts, compact bentonite blocks will be fabricated and placed between the canister and host rock, acting as the EBS. Although the concept of EBS has been proposed and research activities conducted for many years, for example, examining the properties of different types of bentonites, sand-bentonite and natural clay-bentonite mixtures, and at a range of scales, many countries have yet to finalise the exact composition of their specific EBS. Two of the key aspects of the compacted bentonites are their swelling property and hydraulic conductivity. The ability to manufacture synthetic samples with varying compositions and with different dry densities is a prerequisite for high-quality experimental investigations, which can be used to optimize the property parameters of an EBS.

This study, based on the compression of multiple EBS samples, attempts to access the key factors in the manufacture of EBS blocks. Four types of synthetic samples have been fabricated, including 1) 2B samples comprised of 40% of clay (the mass ratio of MX80: kaolinite is 4:1), 50% of sand and 10% of silt; 2) 4B samples compressed from 40% of clay, 30% of sand and 30% of silt; 3) pure MX80 bentonite; and 4) bentonite-sand mixture consists of 40% of MX80 bentonite and 60% of TH1000 sand. Particular focus has been placed on pure MX80 bentonite. 5 samples of bentonite with the same moisture content (26%) were compressed using varying loading stresses at 12.2, 21.3, 30.5, 39.6 and 50 MPa. In contrast, another set of 5 samples of bentonite with moisture contents of 35, 31, 26, 22 and 19% were pressed using the same loading stress (50 MPa). 2B and 4B samples were routinely made at 50 MPa while the bentonite-sand mixtures were compacted at 80 MPa. A vacuum pump was connected to the mould to avoid gas trapping which was found to impact sample compaction. Teflon plates were emplaced at the top and bottom of the mould, which allow gas penetrating and facilitate sample deinstallation.

Geotechnical properties of these samples have been examined. Our observations suggest that the amount of water added and the loading stress jointly control the properties of the synthetic samples. Water affects synthetic sample fabrication in two ways, irrespective of sample composition. First, water has an impact on homogenisation and cohesion of clay materials. Water will unevenly distribute in bentonite if small amount of water is added, which may lead to heterogeneity of the compacted sample; besides, water content controls the viscosity of bentonite and thus the cohesiveness of compacted samples. This impact has been observed for all four types of synthetic samples, but particularly notable for the bentonite-sand mixture. For bentonite-sand mixtures with saturations of around 0.5, the compacted samples present obvious heterogeneity with more sand at the bottom of the cylindrical plugs (Fig. 1a); it is also worth noting that these mixtures were fragile and easily damaged when compressed between fingers. Trimming of these samples also proved difficult, often leaving a rough surface. However, for the mixtures with saturations over 0.9, compacted samples showed very good homogeneity and cohesiveness (Fig. 1b), and could be trimmed with ease. Second, water plays a vital role in resisting loading stress when saturation reached to 1. This was seen in 5 tests which had the same moisture contents but were compacted using varying loading stresses. The results show that all the compacted samples have the same dry density of 1.59 g/cm^3 and the same saturation of 0.98 except the one compressed at 12.2 MPa that gives a dry density of 1.54 and a saturation of 0.89 (Fig. 1c). This observation indicates that higher loading stress (30.5, 39.6 and 50 MPa) will not increase the dry density if too much water is added in the synthetic sample. In such a case, water can resist external stress in confined void space.

Loading stress influences bentonite compaction only when the pore spaces are partially saturated with water. This point is reflected in both varying and constant loading stress tests. In the varying loading stress test, only one specimen had a saturation of less than 0.98. The dry density of this sample was also smaller than the other four (Fig. 1c). Loading stress elevated from 12.2 to 21.3 MPa could assist the increase of saturation in this sample. Similarly, in the constant loading stress test, only one specimen had a saturation less than 0.98 (Fig. 1d), which could have been compacted further if loading stress had been increased to more than 50 MPa. It is noteworthy that there is no theoretical relationship between loading stress and dry density if samples were only partially saturated. Thus, empirical higher loading stress and fully saturation are suggested for synthetic sample manufacturing. In this way, EBS material properties can be controlled in order to examine their influence on EBS behaviours when exposed to different ambient conditions.

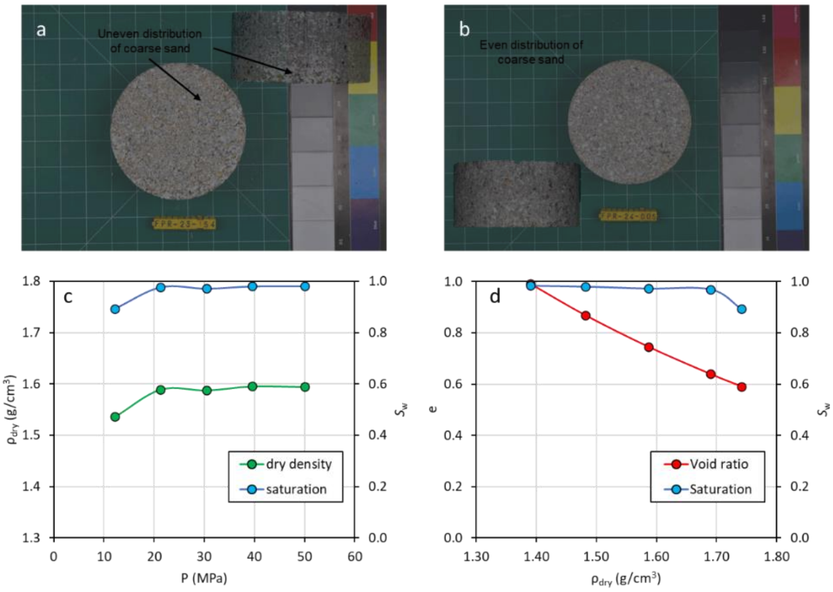

Figure 1 – Photos of compacted bentonite-sand mixtures and geotechnical parameters of MX80 bentonite pressed at different conditions. (a) Uneven distribution of coarse sand particles at the bottom of the cylindrical specimen, (b) even distribution of sand and clay, (c) samples with different dry densities (ρ_{dry}) and water saturations (S_w) were compacted at different loading stresses, (d) samples with different void ratios (e) and water saturations (S_w) were compressed at an identical loading stress of 50 MPa.